Low-β insertions for the VLHC
(draft)

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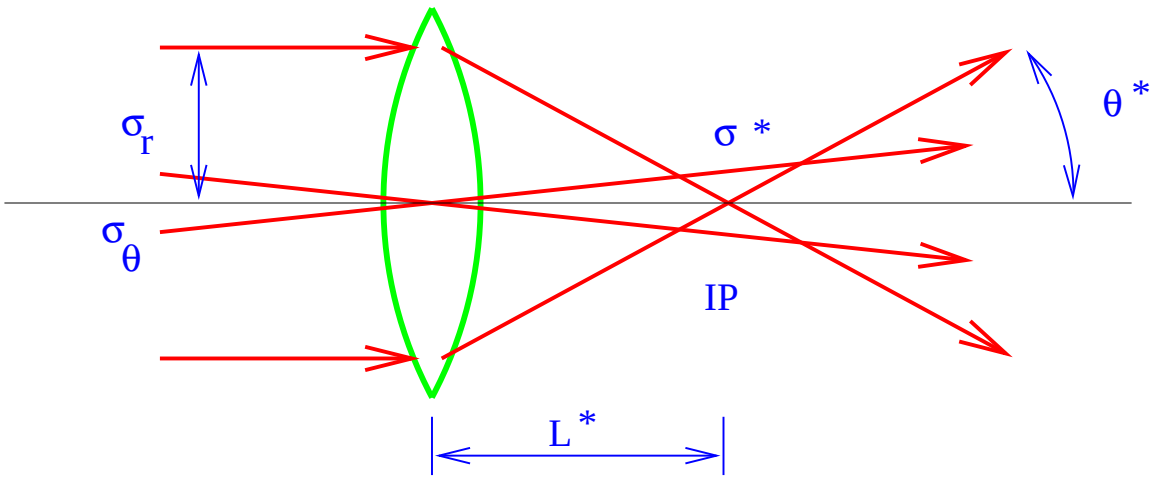
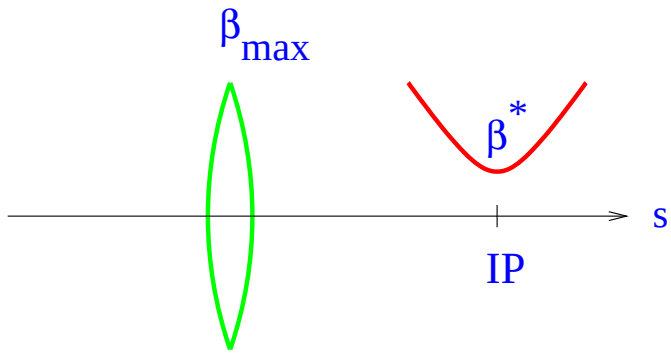
- **Scaling laws for low-β insertions**
  - What is min σ^* for given ε_n, B_{critical} and θ_{crossing} ?
  - Chromaticity due to final quads
  - Global and local chromaticity correction
- **VLHC ring with two $\beta^* = 0.1$ m IP**
  - 90° ring lattice
  - IR lattice
  - System of losses localisation
  - Chromaticity issues
  - Unequal β_x^*, β_y^* and problems of doublet optics
  - Beam separation
  - Crossing angle
  - Anomalous dispersion due to crossing
  - Closed orbit sensitivity to final quad motion
- **Things to do**

What is low-β^* ?



$\sigma_r \sigma_\theta = \varepsilon$ $\qquad$ $\sigma^* = \sigma_\theta \, L^* = \frac{\varepsilon \, L}{\sigma_r} = \frac{\varepsilon}{\theta^*}$ $\qquad$ $\theta^* = \frac{\sigma_r}{L^*}$

in terms of β:

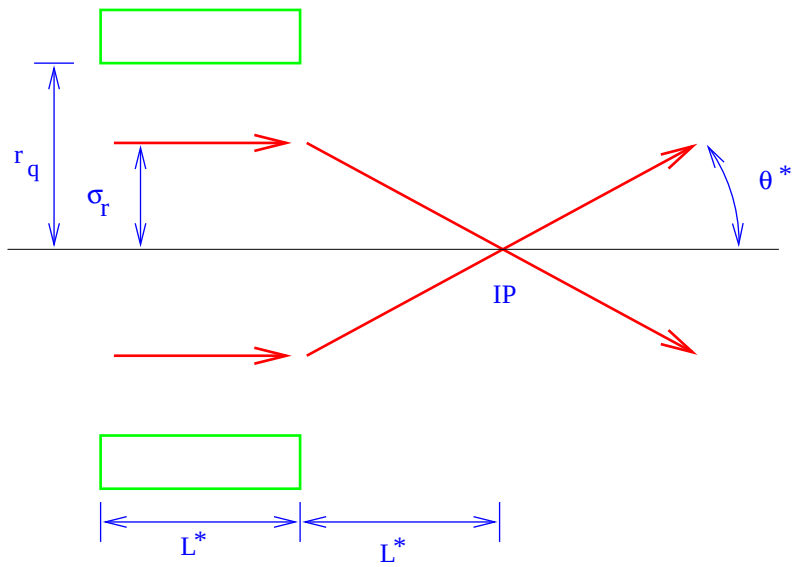


$\beta = \beta^* + \frac{s^2}{\beta^*}$ $\qquad$ $\sigma^* = \sqrt{\varepsilon \beta^*}$ $\qquad$ $\theta^* = \sqrt{\varepsilon / \beta^*}$

$\beta_{\max} \approx L^{*2} / \beta^*$

What is min σ^* for given ε and B_{crit}? (simple scaling laws)

or What is max θ^* ?

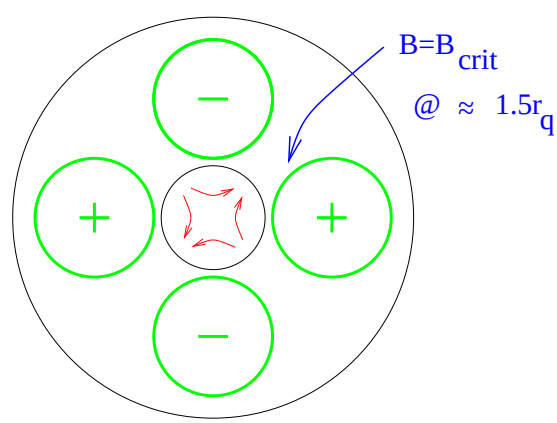


Quad aperture: $r_q = n\,\sigma_r = n\theta^* L^*$, need $n > 1$

Focal length of quad: $F = \frac{B\rho}{GL^*}$, $(B\rho = pc/e)$

Need $F \approx L^*$

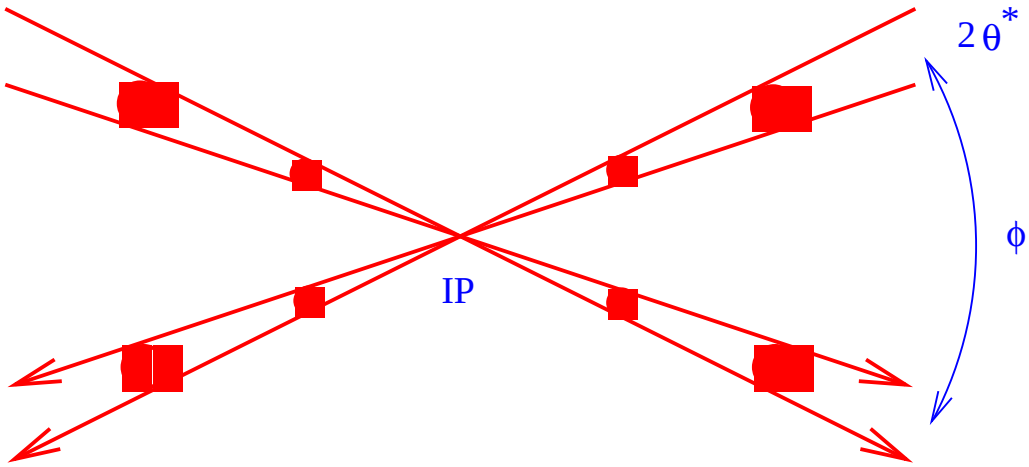
Gradient of SC quad
$G \approx \frac{B_{\text{crit}}}{1.5 r_q}$



$\Rightarrow$ max $\theta^* \approx \frac{L^*\,B_{\text{crit}}}{1.5\,n\,B\rho}$

$\Rightarrow$ min $\sigma^* \approx \frac{1.5\,n\,B\rho\varepsilon}{L^*\,B_{\text{crit}}}$

Crossing angle and scaling laws



Crossing angle $\phi = m\,\theta^*$, need $m > 2$

$\Rightarrow$ scaling

$$\min\ \sigma^* \approx \frac{1.5\,n\,m\,B\rho\varepsilon}{L^*\ B_{\mathrm{crit}}}$$

$$\Rightarrow \qquad \sigma^* \downarrow \qquad \text{if} \qquad L^* \uparrow$$

An example

$\varepsilon = 1.33$ mm·mrad

$B_{\text{crit}} = 10$ T

$B\rho = 1.66 \cdot 10^5$ T·m

$n = 3$ (quad aperture clearance)

$m = 5$ (crossing angle clearance)

then scaling $\sigma^* \approx \frac{1.5\, n\, m\, B\rho\varepsilon}{L^*\, B_{\text{crit}}}$

gives $\sigma^* \approx \frac{10\mu m}{L^*(m)}$

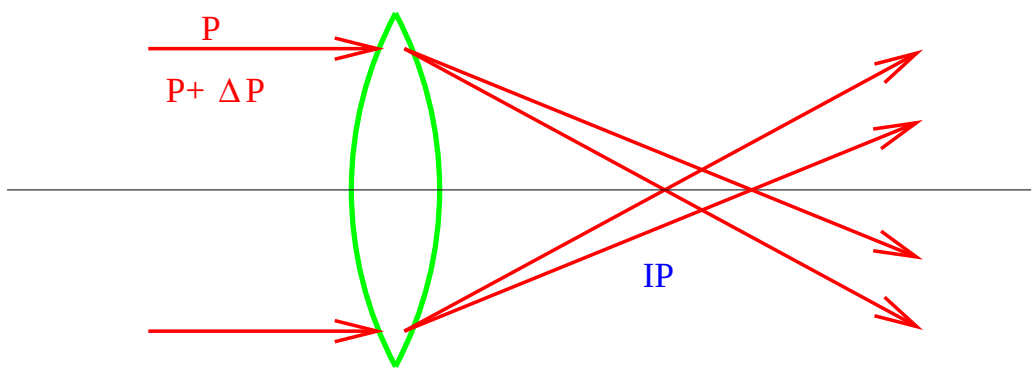
or $\beta^* \approx \frac{4m}{L^{*\,2}(m)}$

(in reality we use doublet or triplet focusing and the coefficients are different)

$\sigma^* \propto 1/L^*$

What's wrong with $L^* \uparrow$?

An example. Chromaticity.



$\Delta\sigma^* \approx \theta^* L^* \Delta P/P$

$\Rightarrow \Delta\sigma^*/\sigma^* \approx \frac{L^*}{\beta^*}\Delta P/P$

if we follow scaling $\sigma^* \propto \varepsilon/L^*$

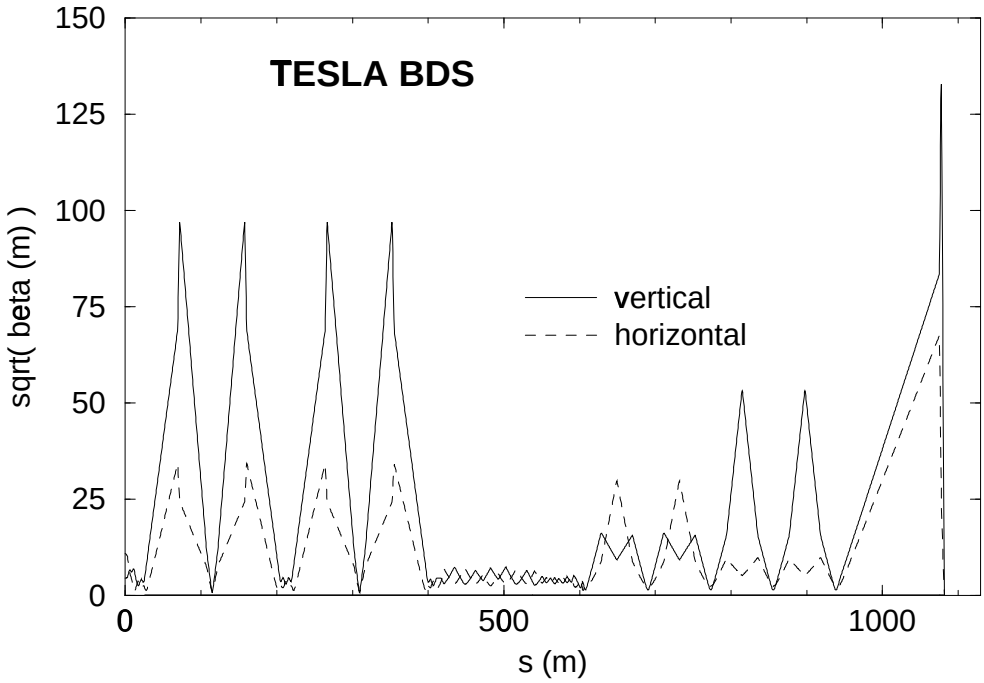
then $\Delta\sigma^*/\sigma^* \propto \frac{L^{*3}}{\varepsilon}\Delta P/P$

$\frac{L^*}{\beta^*}$ — chromaticity

$\frac{L^*}{\beta^*}\Delta P/P << 1$ — global correction of linear chromaticity

$\frac{L^*}{\beta^*}\Delta P/P >> 1$ — local correction of chromaticity

Low β^* may require local chromatic correction. Example.



TESLA Linear Collider Beam Delivery System (collimation + tuning section + chromatic correction section + final focus).

Typical for all LCs: $\beta^* \propto 0.1$ mm, $L^* \propto 3$ m

$L^*/\beta^* \propto 30000$, $\Delta P/P \propto 10^{-3}$ – 10^{-2}

VLHC low-β with $\beta_x^* = \beta_y^* = 0.1$ m

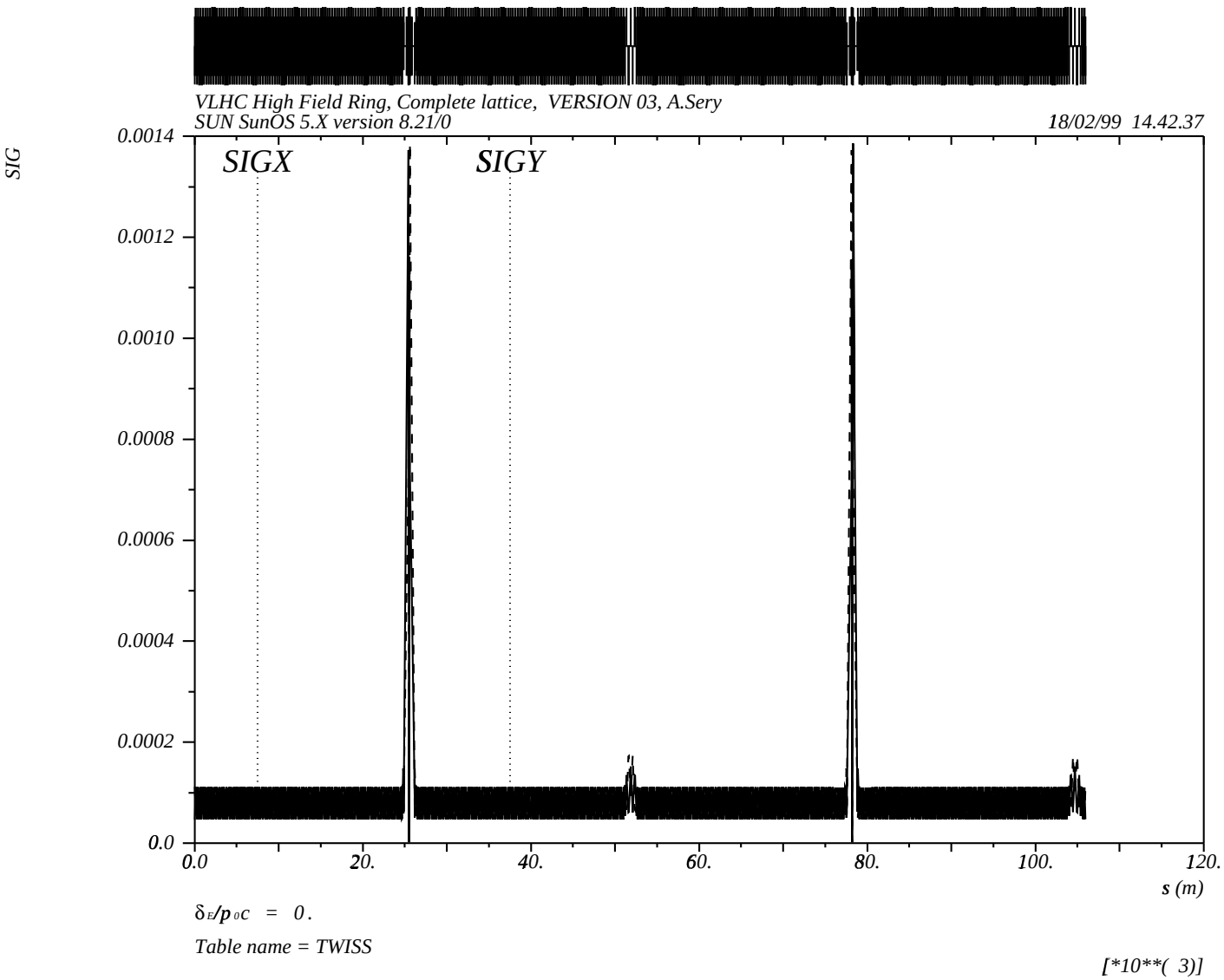
$L^* = 25$ m

$L^*/\beta^* \approx 250$ – global correction of linear chromaticity (local of nonlinear)

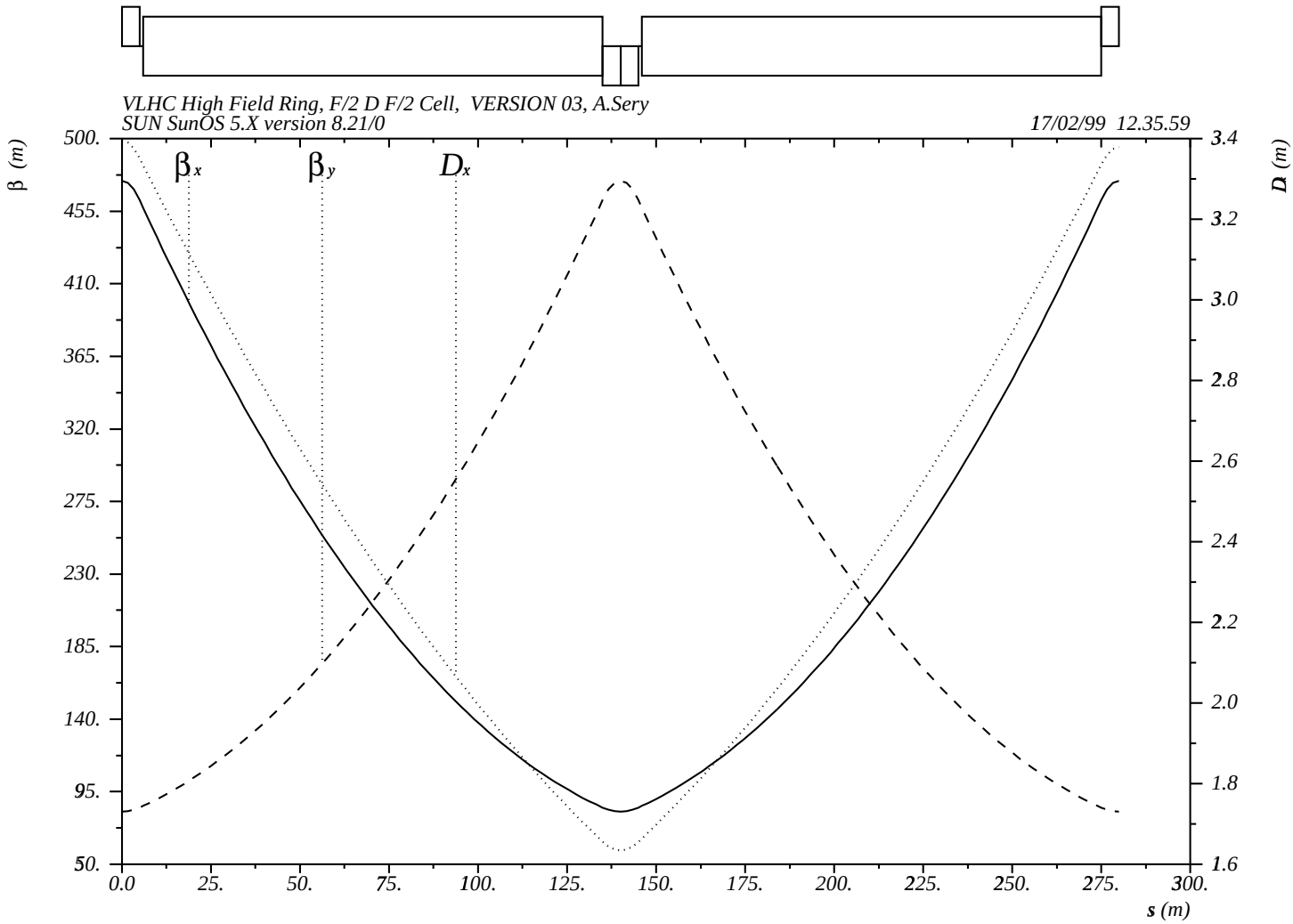
Triplet optics, 370 T/m quads

IR optics matched to high field ring lattice

VLHC high field (11.6 T) ring with two $\beta^* = 0.1$ m IP,
system of losses localization
and injection insertion.



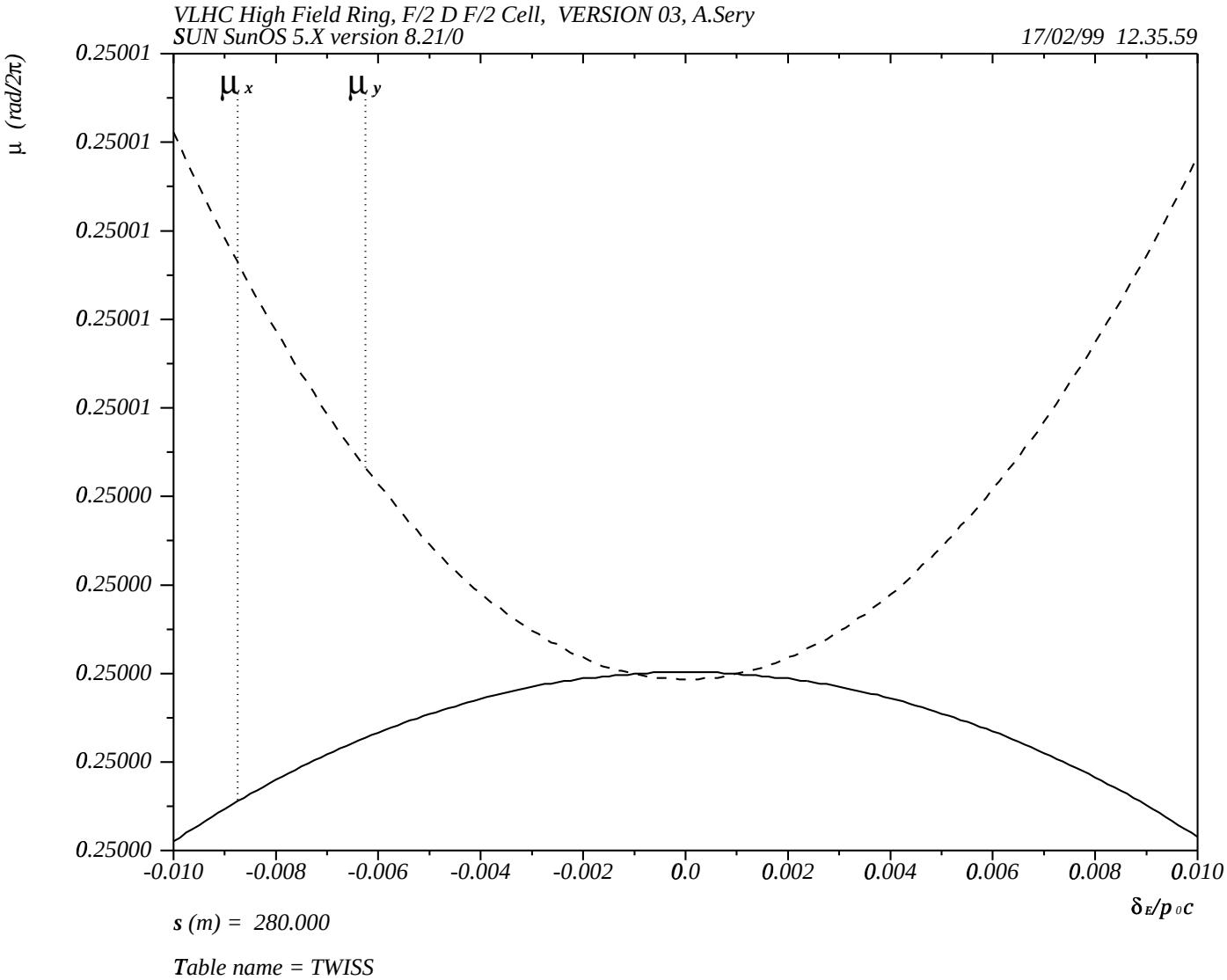
VLHC high field complete ring, $L_{\rm tot} = 105.95$ km. Beam size for $\varepsilon_n = 1.33$ mm*mrad (rms).



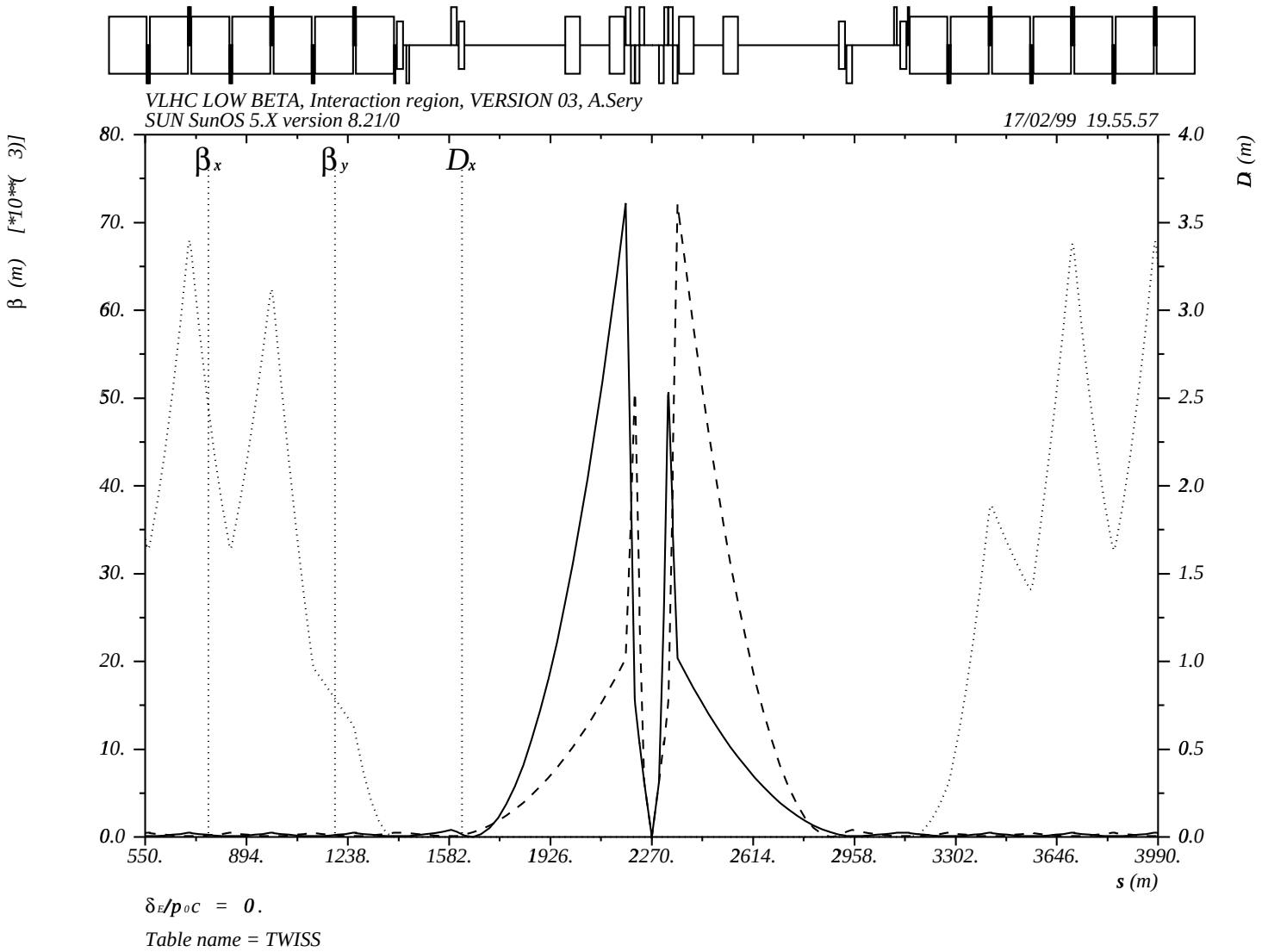
90 degree F/2ODOF/2 cell for the high field VLHC.

```
QRF1 : QUADRUPOLE, L= 5, K1= 1.0E-03     ! ~ 173 T/m  supercond.
QRD1 : QUADRUPOLE, L= 5, K1=-1.0E-03     !
SRF1 : SEXTUPOLE , L= 1, K2= 3.2E-03     !
SRD1 : SEXTUPOLE , L= 1, K2=-6.4E-03     !
BR1  : SBEND     , L= 129  , ANGLE =  PI/350   ! ~ 11.6 T   supercond.

RING_FDF : LINE=(QRF1,SRF1,BR1,2*QRD1,SRD1,BR1,QRF1)
RING_FDF_0: BETA0, BETX = 474 , BETY =  82 , DX = 3.4
!definition: K1=B_0/a/Br, K2/2=B_0/a^2/Br, L in meters; Br=1.667E+05 T*m
```

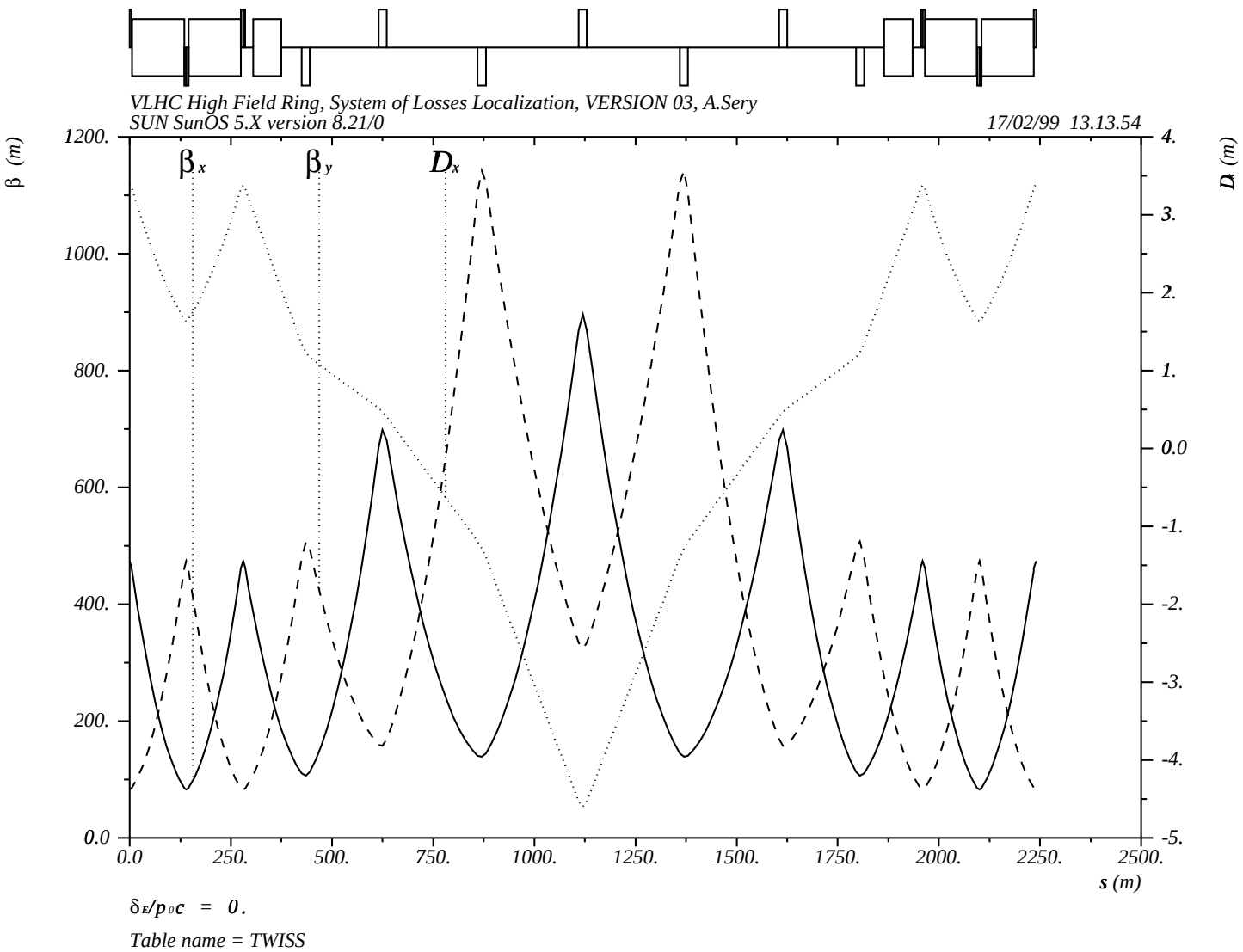


Phase advance per cell of the high field VLHC ring.



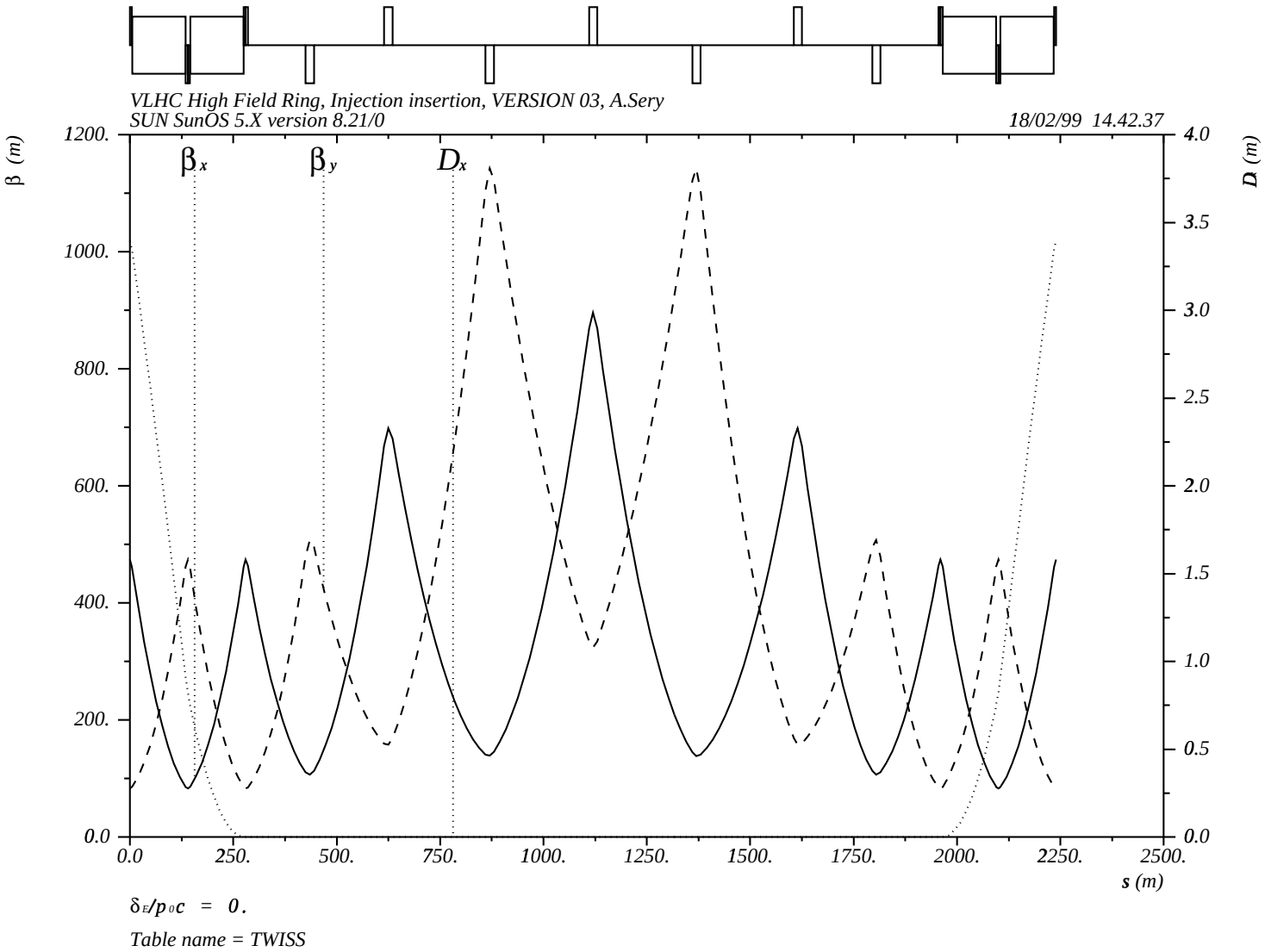
VLHC interaction region with $\beta^* = 0.1$ m.

(Beam separators are off).

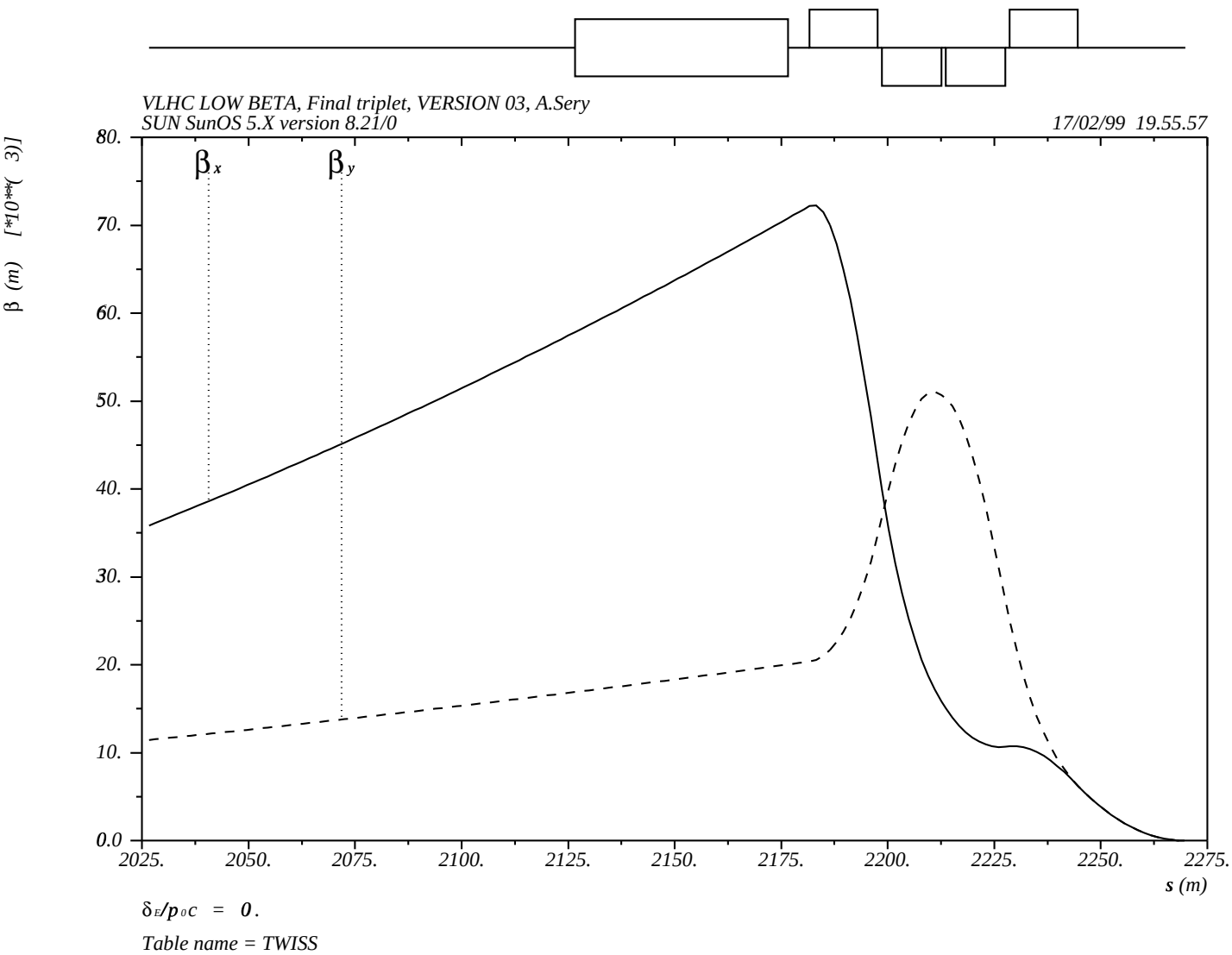


System of losses localization for the high field VLHC.

```
QM5 : QUADRUPOLE, L =  5 , K1= .87E-03   ! ~ 146T/m supercond.
QM6 : QUADRUPOLE, L = 20 , K1=-.40E-03   ! ~ 68 T/m normal cond.
QM7 : QUADRUPOLE, L = 20 , K1= .34E-03   !          normal cond.
QM8 : QUADRUPOLE, L = 20 , K1=-.25E-03   !          normal cond.
QM9 : QUADRUPOLE, L = 20 , K1= .29E-03   !          normal cond.
   OM1 : DRIFT, L = 20 ;    OM3 : DRIFT, L = 170 ;    OM5 : DRIFT, L = 230
   OM2 : DRIFT, L = 50 ;    OM4 : DRIFT, L = 225
BM3 : SBEND , L = 70, ANGLE = .79E-03    ! ~ 1.9T normal cond.
   M_LOSS_L : LINE=(QRF1,SRF1,BR1,QRD1,QRD1,SRD1,BR1,QRF1,  &
                                    QM5,OM1,BM3,OM2,QM6,OM3,QM7,OM4,QM8,OM5)
M_LOSS   : LINE=(M_LOSS_L,QM9,-M_LOSS_L)
```



Injection and instrumentation insertion of the high field VLHC ring.

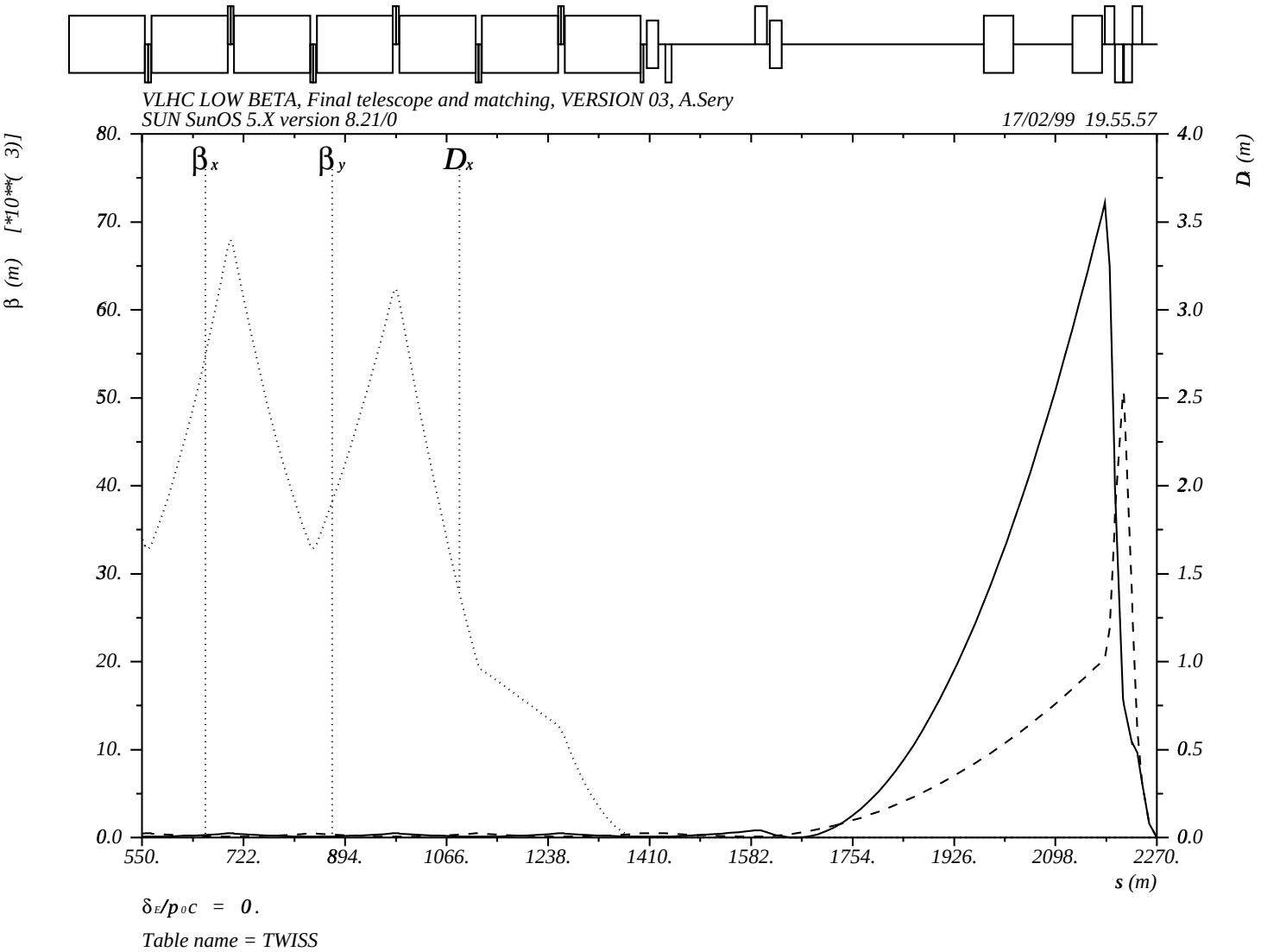


Final triplet of the VLHC low-β with $\beta^* = 0.1$ m.

```
! Final triplet, superconducting quads:
  QFF1 : QUADRUPOLE, L = 16 , K1=  2.2E-03  ! ~ 371 T/m
  QFF2 : QUADRUPOLE, L = 16 , K1=  2.2E-03  !
  QFD1 : QUADRUPOLE, L = 14 , K1= -2.2E-03  !
  QFD2 : QUADRUPOLE, L = 14 , K1= -2.2E-03  !
     DF1  : DRIFT, L = 25;      DF2  : DRIFT, L = 1
     DF3  : DRIFT, L = 100;     DF4  : DRIFT, L = 5
! Bends for beam separation
  BF1 : SBEND , L = 50.0  , ANGLE =  5.0E-04  ! ~ 1.66 T  normal cond.
  BF2 : SBEND , L = 50.0  , ANGLE = -5.0E-04  !
FIN_TEL:LINE=(IP,DF1,QFF1,DF2, QFD1,DF2,QFD2,DF2,QFF2,DF4,BF1,DF3,BF2)
```

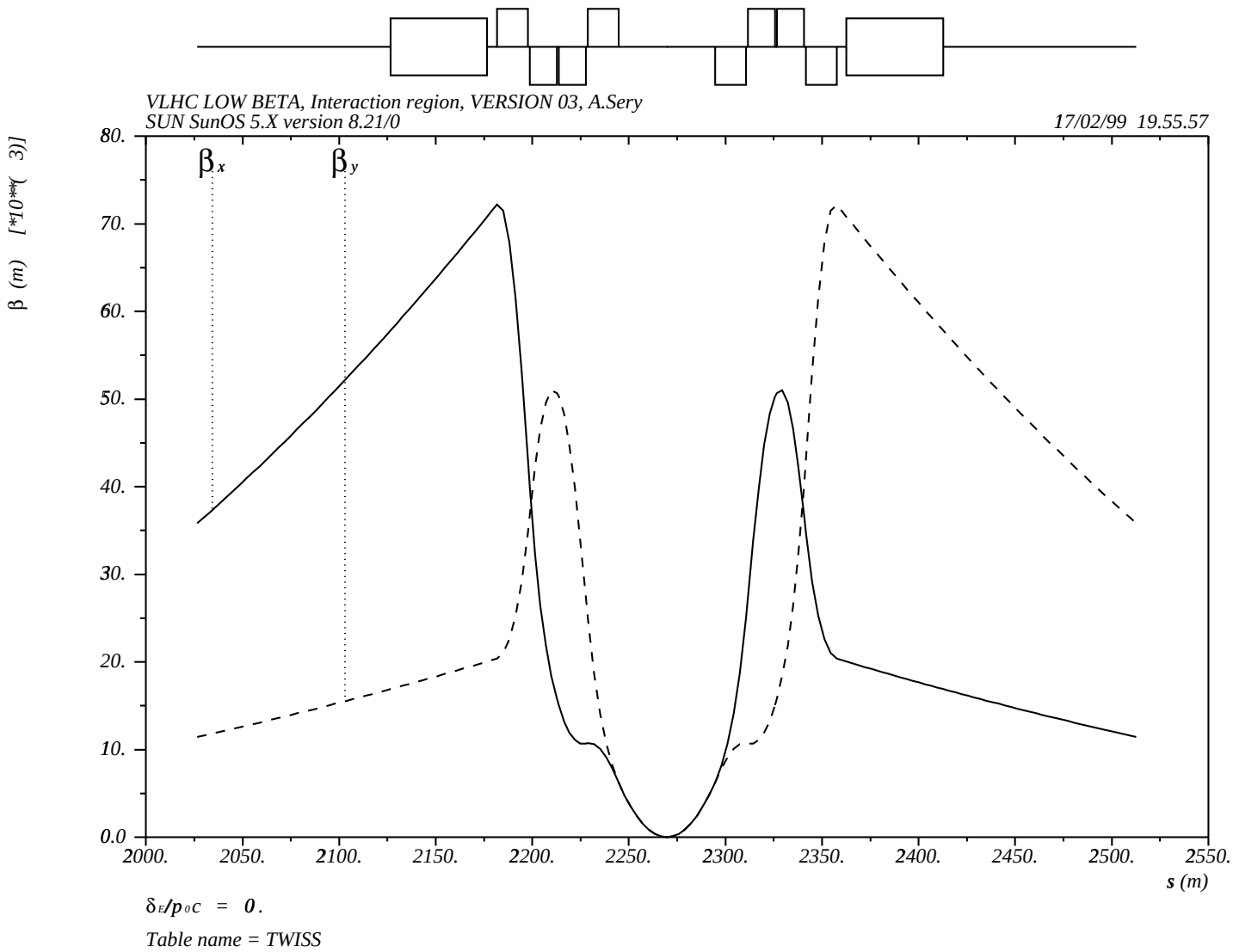
Scaling of LHC final quad

Inner coil aperture (mm)	70	$\rightarrow$	50
Material	NbTi	$\rightarrow$	Nb_3Sn
Operating quadrupole gradient (T/m)	235	$\rightarrow$	370 ?



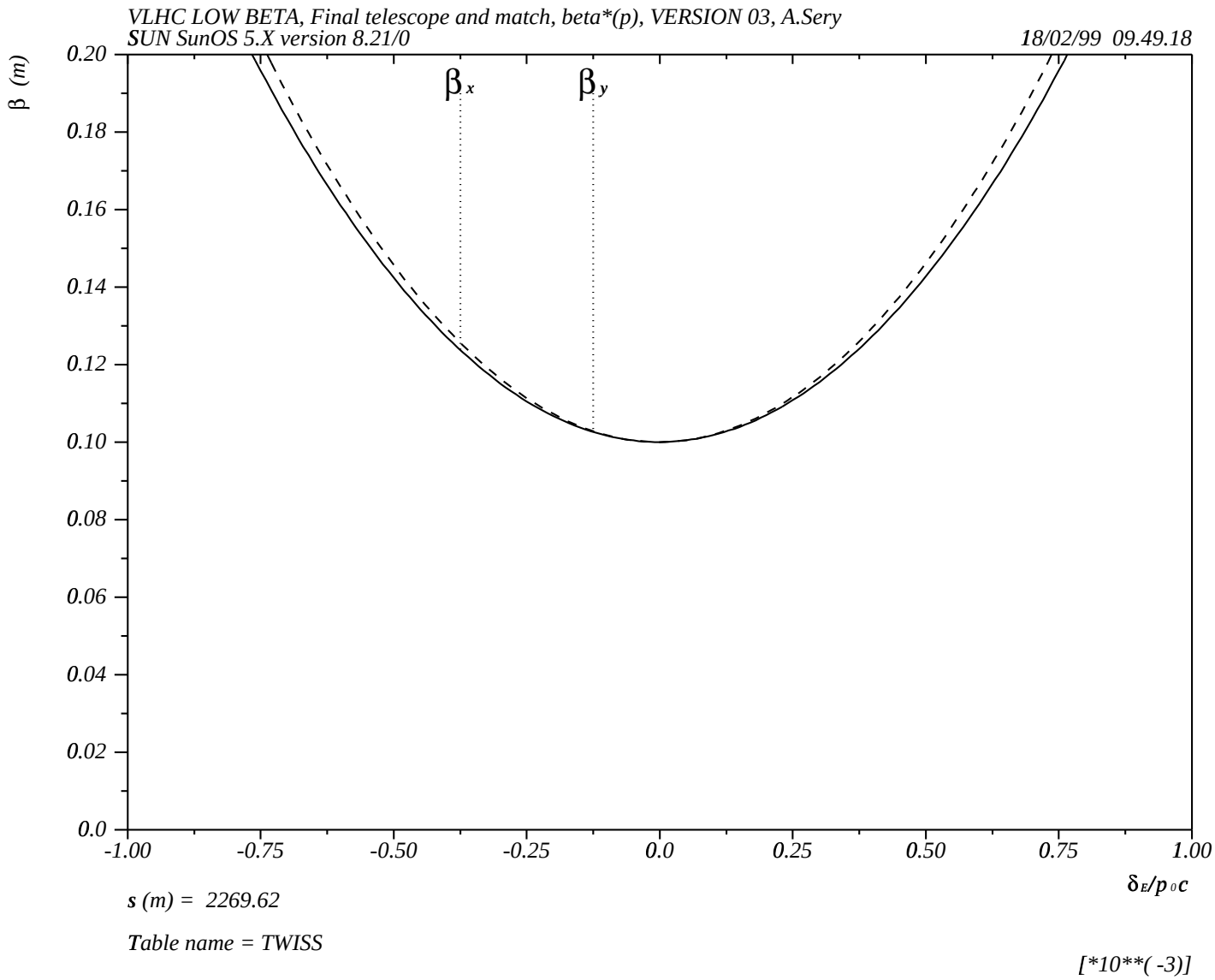
Final telescope and matching. (Beam separators are off).

```
DM1 : DRIFT, L = 342;   DM1_A : DRIFT, L = 5;  DM2 : DRIFT, L = 142
DM3 : DRIFT, L = 12 ;   DM3_A : DRIFT, L = 5
HVKX1 : KICKER,L=20 ; HVKX2 : KICKER
HVKY1 : KICKER,L=20 ; HVKY2 : KICKER
QMT1  : QUADRUPOLE, L = 20 , K1=  1.1E-03
QMT2  : QUADRUPOLE, L = 10 , K1= -4.8E-04
QMT1N : QUADRUPOLE, L = 20 , K1= -1.1E-03
QMT2N : QUADRUPOLE, L = 10 , K1=  4.8E-04
MATCH_LINE    : LINE=(DM1,HVKY1,DM1_A,QMT1,DM2,QMT2,DM3,HVKX1,DM3_A)
TEL_AND_MATCH : LINE=(FIN_TEL,MATCH_LINE,-MATCH_PSI)
MATCH_AND_TEL : LINE=(-TEL_AND_MATCH)
```



Beta functions at the VLHC IP with $\beta^* = 0.1$ m.

Optics is symmetrical for p $\rightarrow$ $\leftarrow$ p



$\beta^*(p)$ for final telescope and matching of the VLHC.

Linear chromaticity

Bare VLHC ring (no IP, no insertions):

uncorrected: $Q'_x = -113.3$, $Q'_y = -113.3$

if corrected globally, requires:

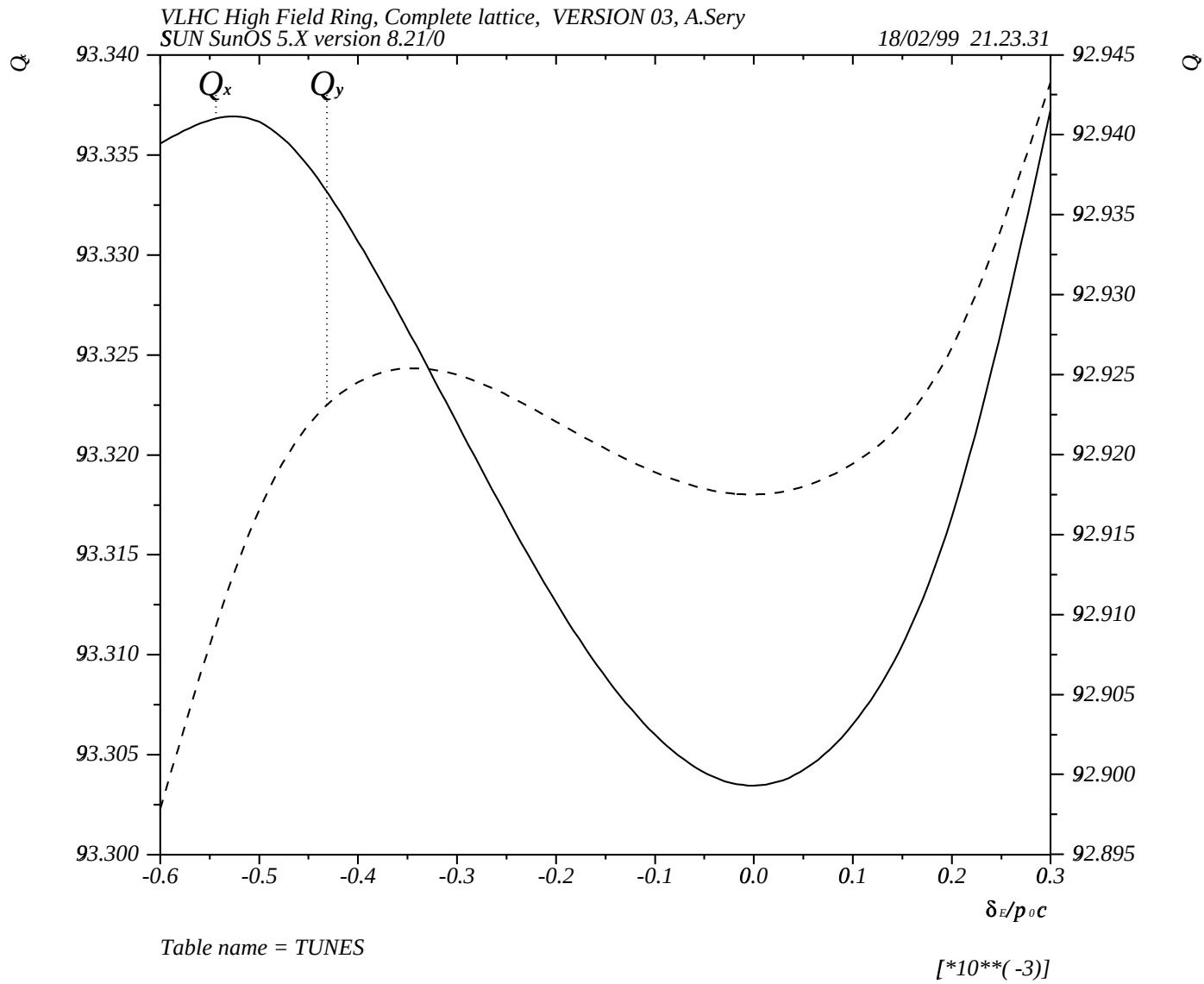
```
SRF1 : SEXTUPOLE, L = 1.0, K2=  3.2E-03
SRD1 : SEXTUPOLE, L = 1.0, K2= -6.4E-03
```

Complete VLHC ring (two IP, two insertions):

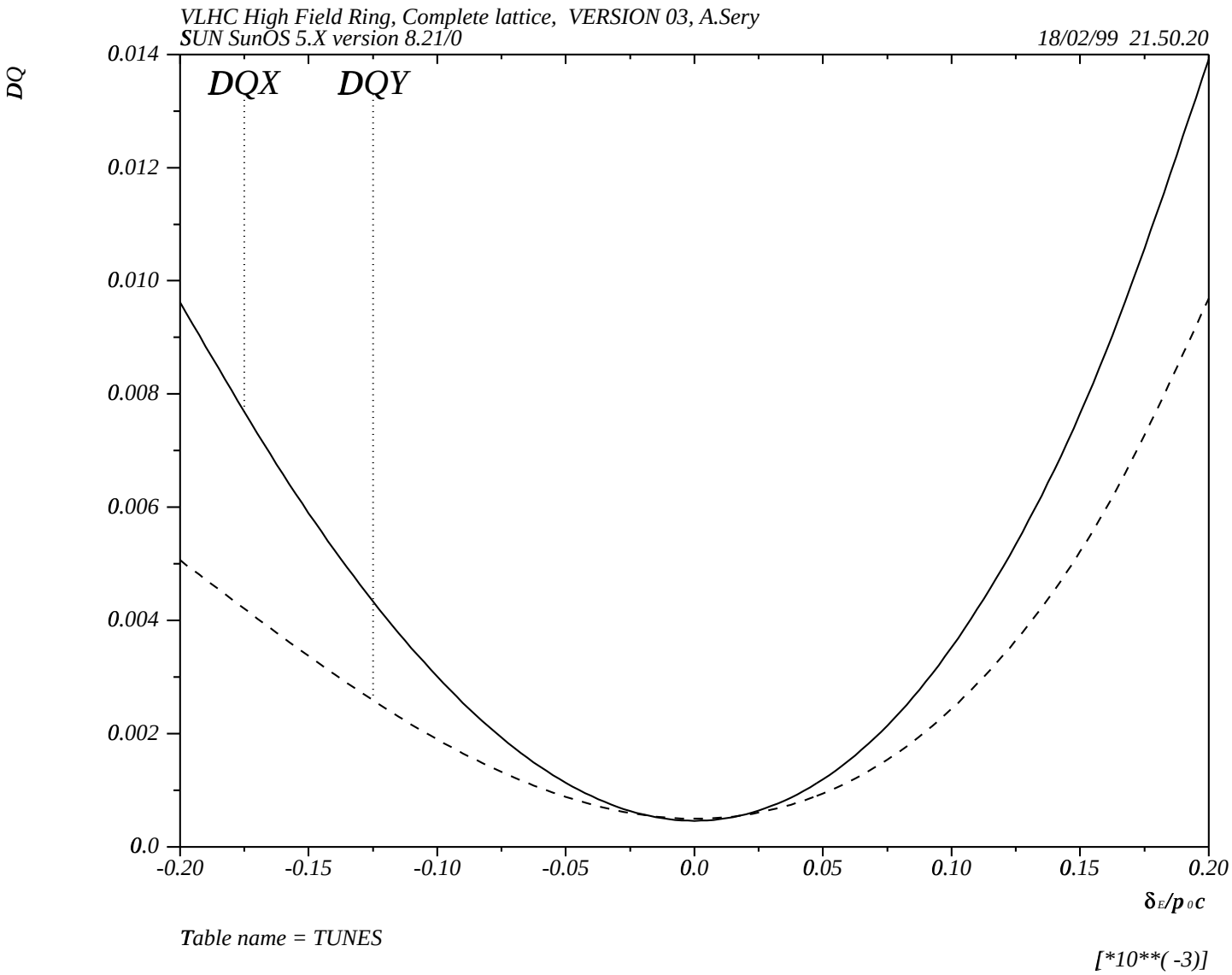
uncorrected: $Q'_x = -539.7$, $Q'_y = -539.5$

if corrected globally, requires:

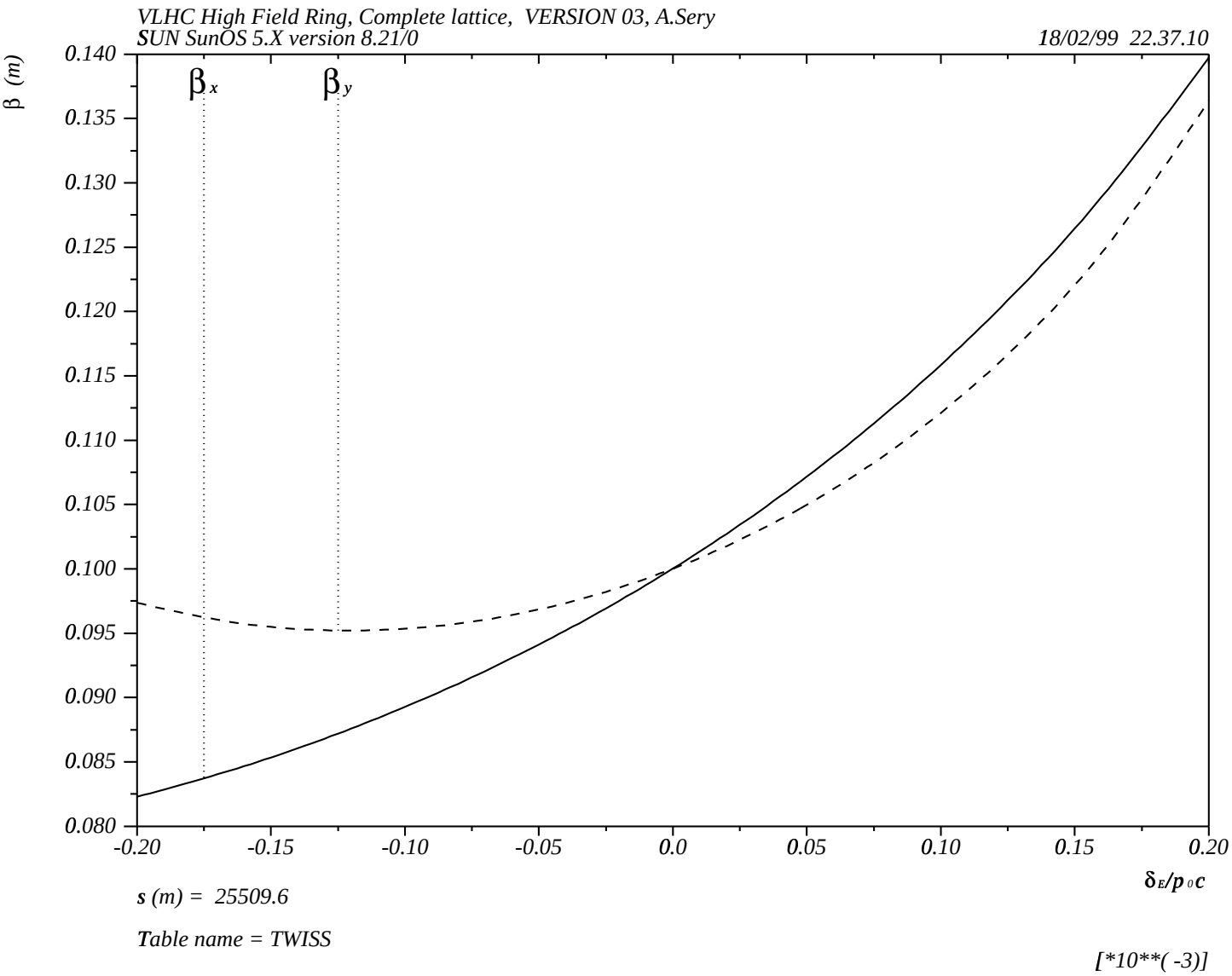
```
SRF1 : SEXTUPOLE, L = 1.0, K2=   1.5E-02
SRD1 : SEXTUPOLE, L = 1.0, K2=  -3.1E-02
```



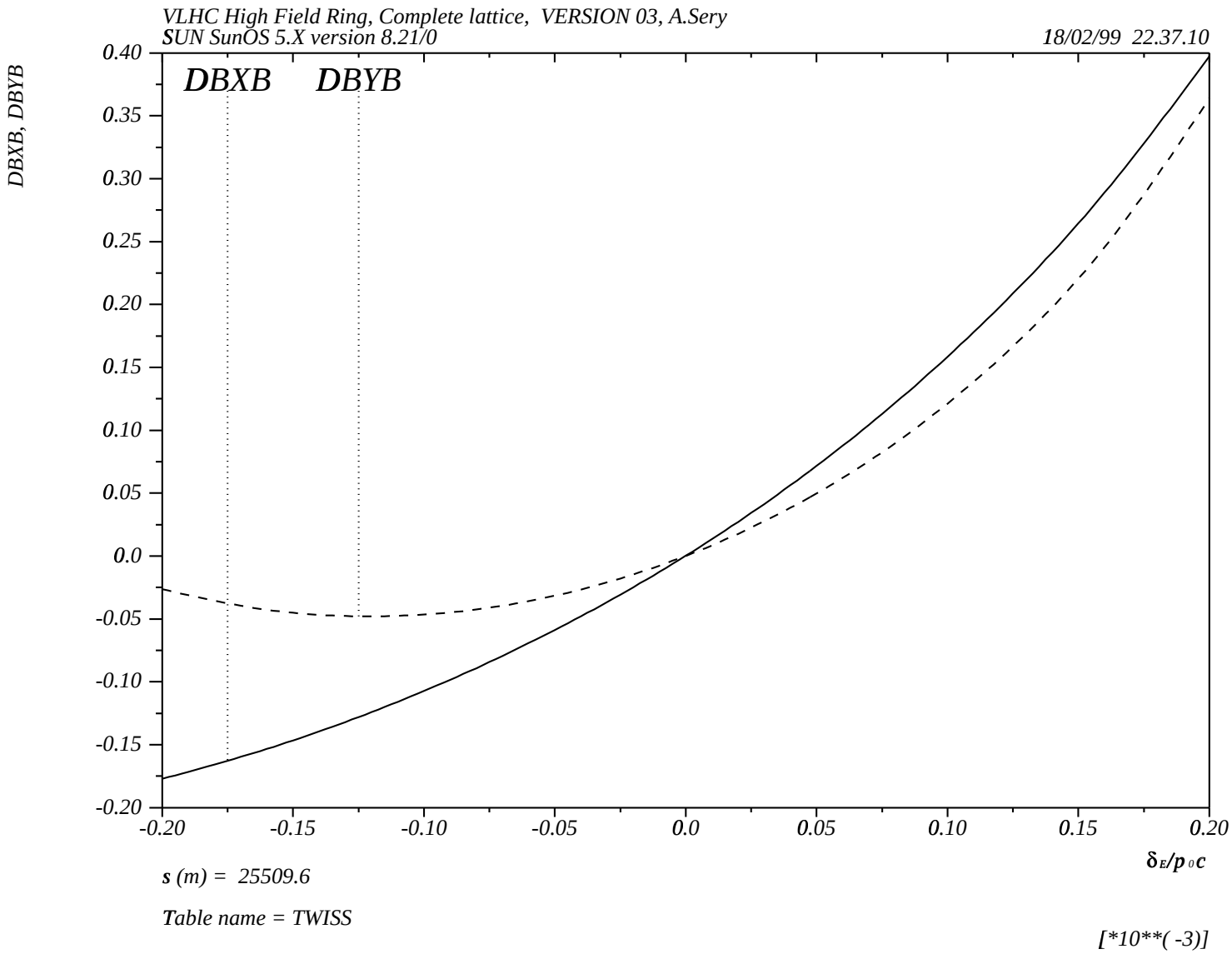
Complete VLHC ring, nonlinear chromaticity.
Q_x, Q_y vs $\Delta P/P$.



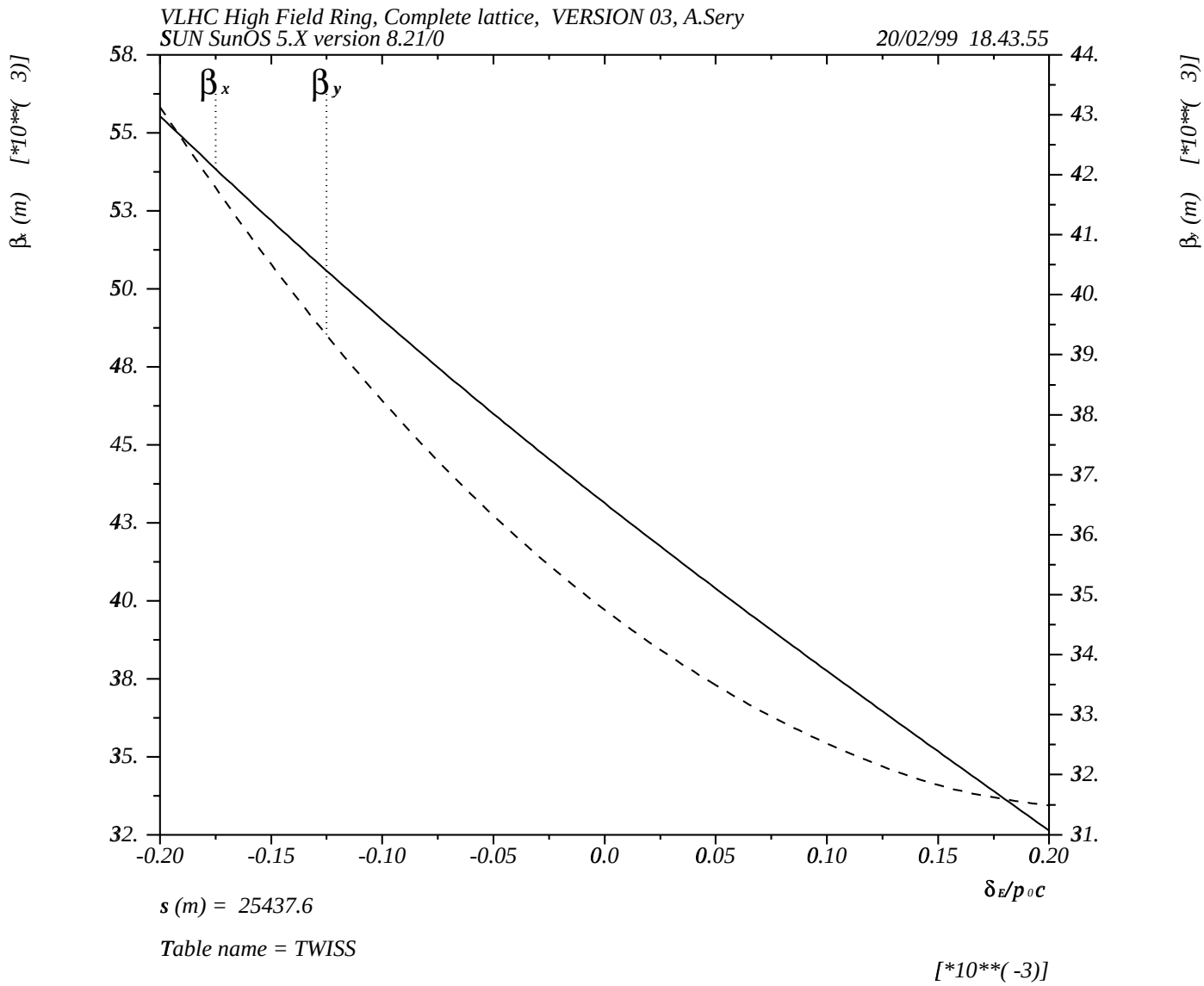
Complete VLHC ring, nonlinear chromaticity.
ΔQ_x, ΔQ_y vs $\Delta P/P$.



Complete VLHC ring, β^* at IP[1] vs $\Delta P/P$.

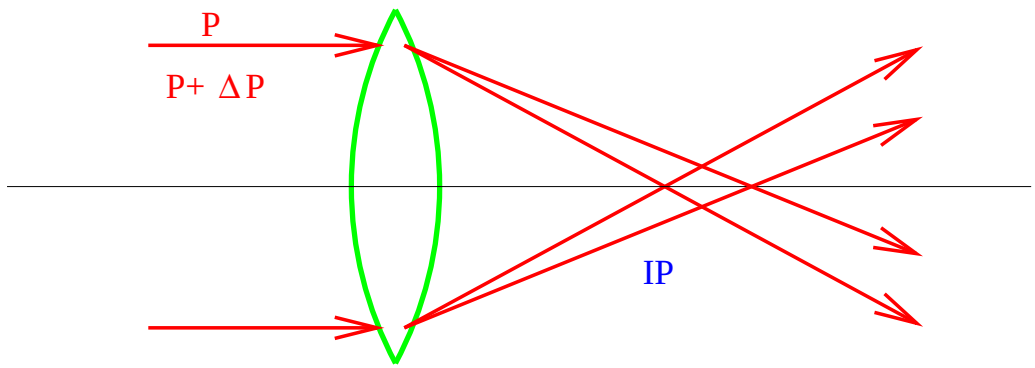


Complete VLHC ring, $\Delta\beta^*/\beta_0^*$ at IP[1] vs $\Delta P/P$.



Complete VLHC ring, β at QFF2[1] vs $\Delta P/P$.

Correction of 2nd order chromaticity



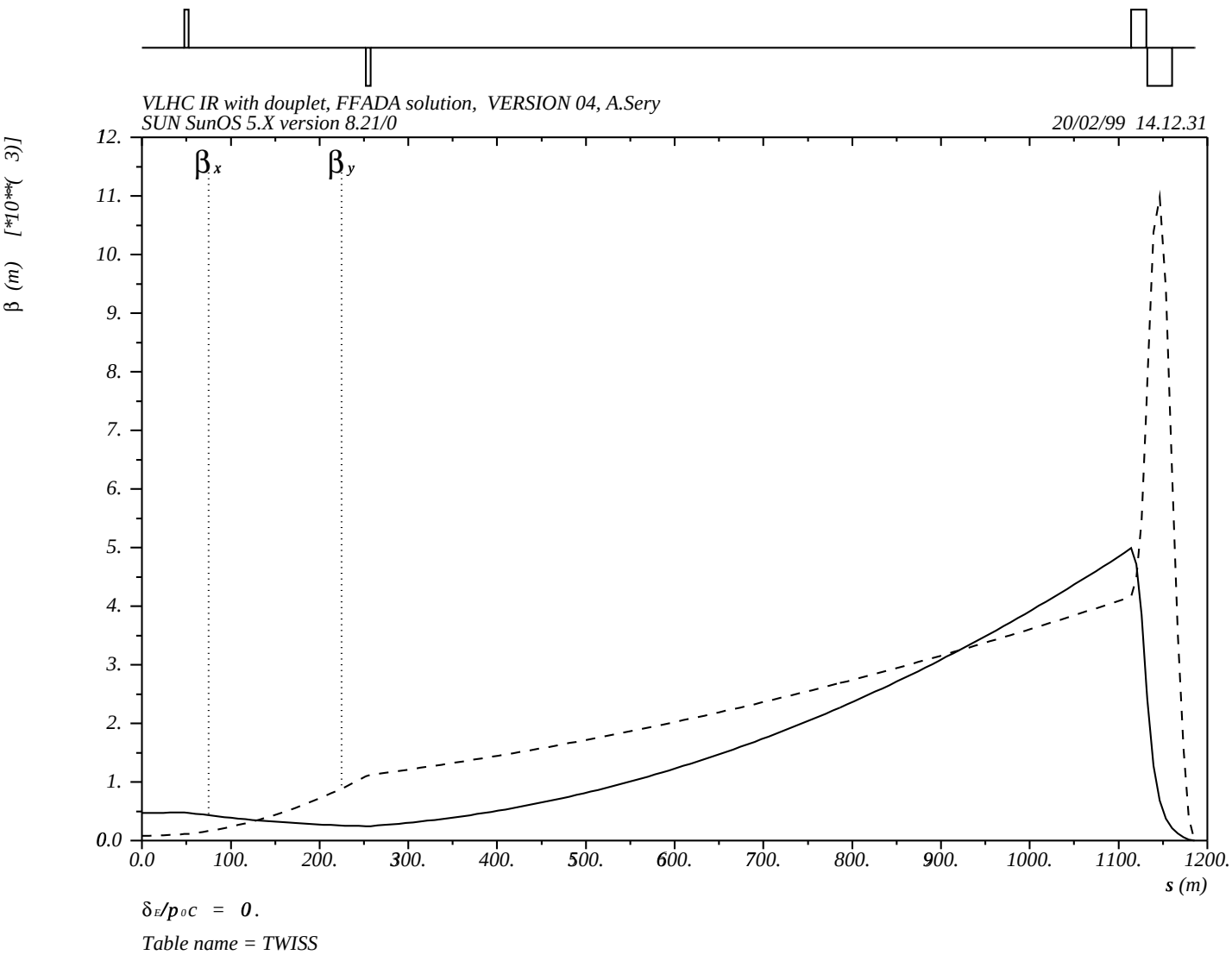
1-st order chromaticity

if $d\beta/dp$ in the lens $\Rightarrow$ 2nd order chromaticity, etc.

Can be compensated if two identical IP are in $\pi/2+\pi n$ phase.

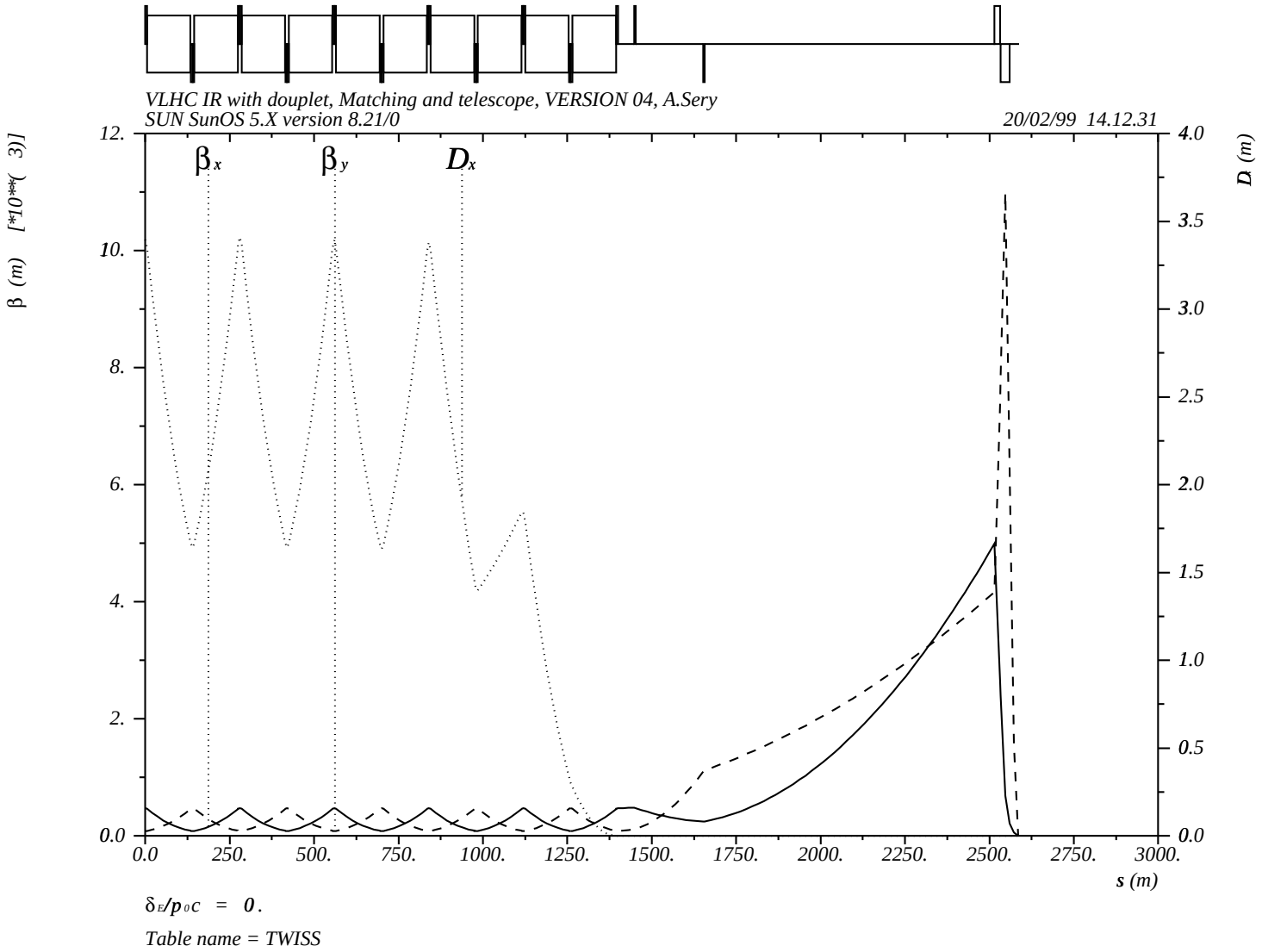
$\Rightarrow$ need to place two IR close, not as in considered VLHC scheme

+ local correction in nearby cells of the arcs

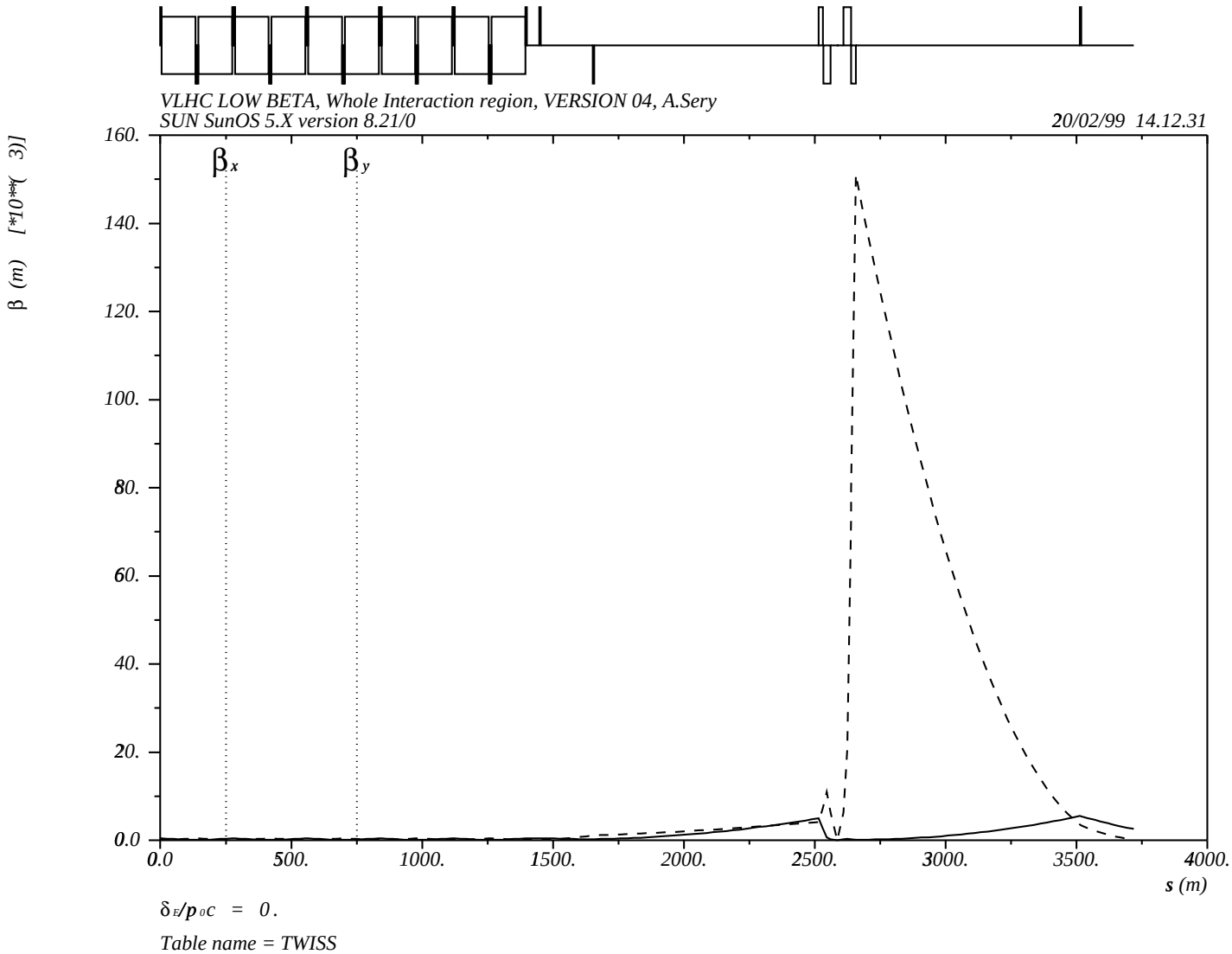


Doublet optics for VLHC, $\beta_x^* = 3$ m, $\beta_y^* = 0.1$ m.

```
!********************** Final Doublet and telescope ********************
! solution by FFADA  (Final Focus Automatic Design & Analysis, O.Napoly)
IP: MARKER
D1: DRIFT, L=47 ;   D2: DRIFT, L=190 ;  D3: DRIFT, L=850
D4: DRIFT, L=1  ;   D5: DRIFT, L=25
Q1: QUADRUPOLE, L=5 , K1= .46E-3
Q2: QUADRUPOLE, L=5 , K1=-.54E-3
Q3: QUADRUPOLE, L=17, K1= .21E-2        ! ~ 370 T/m
Q4: QUADRUPOLE, L=28, K1=-.21E-2
TELE: LINE=(D1,Q1,D2,Q2,D3,Q3,D4,Q4,D5,IP)
```

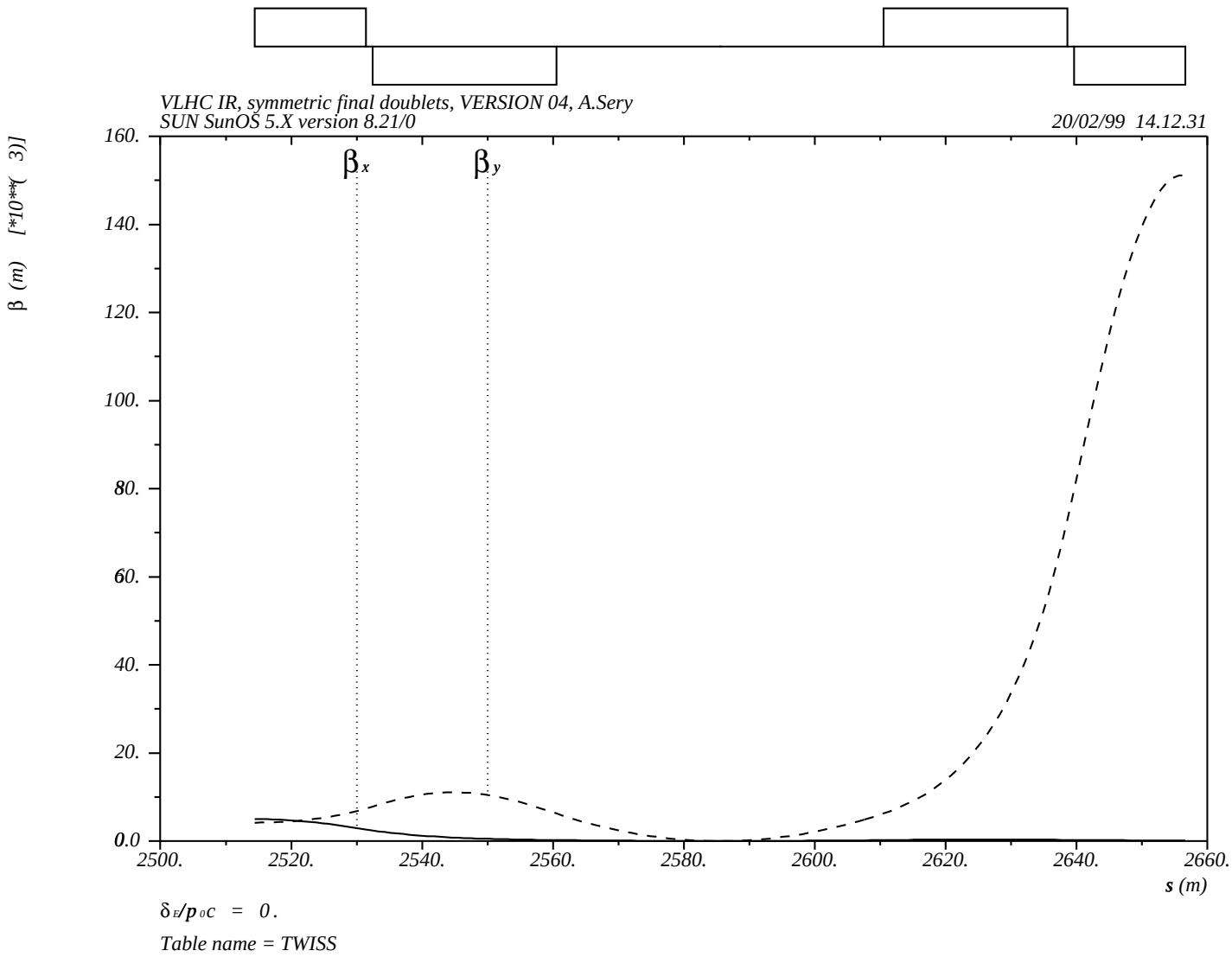


Doublet optics for VLHC. Matching and telescope.



Doublet optics for VLHC, $\beta_x^* = 3$ m, $\beta_y^* = 0.1$ m.

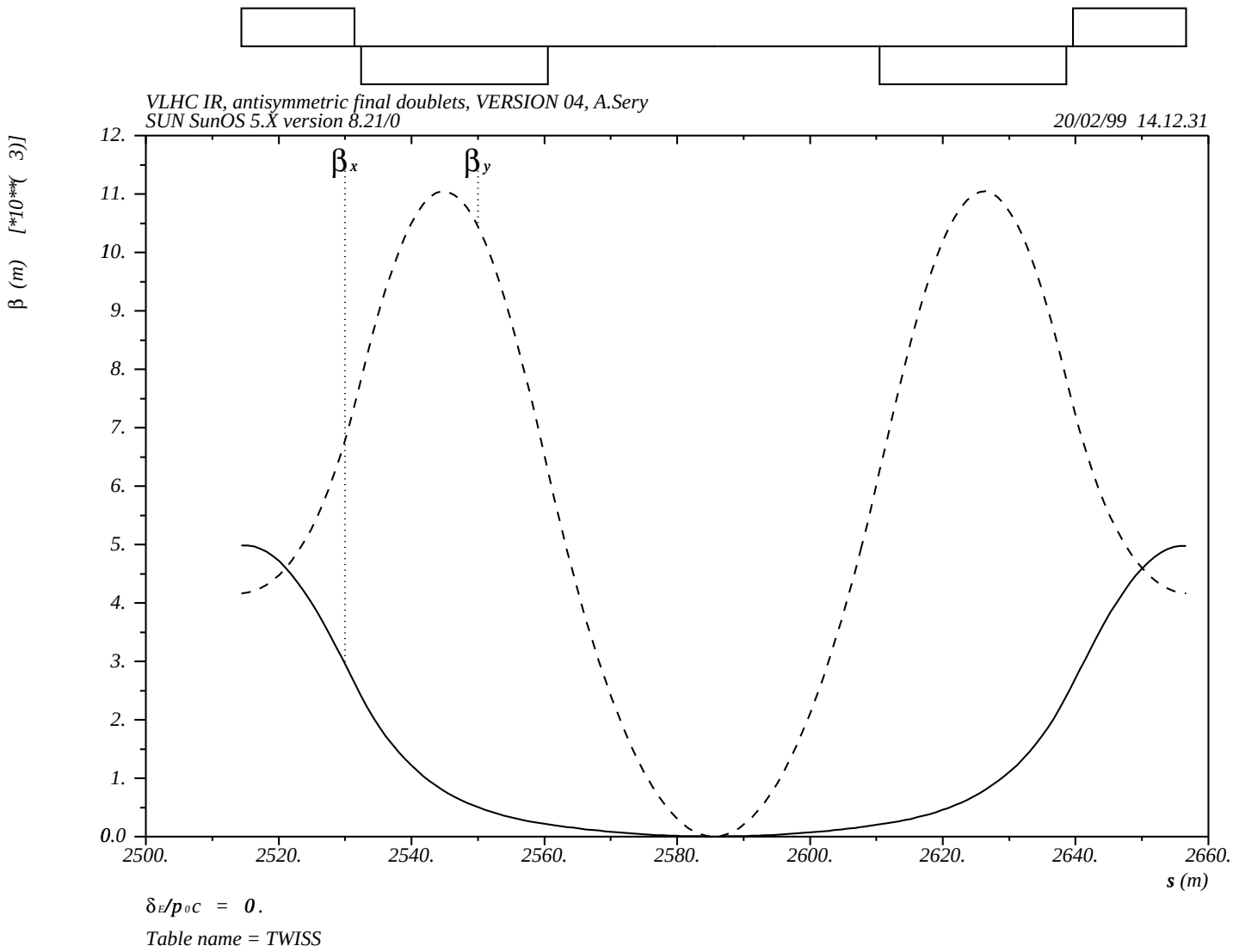
Optics is symmetrical for p $\rightarrow$ $\leftarrow$ p



Doublet optics for VLHC, $\beta_x^* = 3$ m, $\beta_y^* = 0.1$ m.

Symmetrical for p $\rightarrow$ $\leftarrow$ p

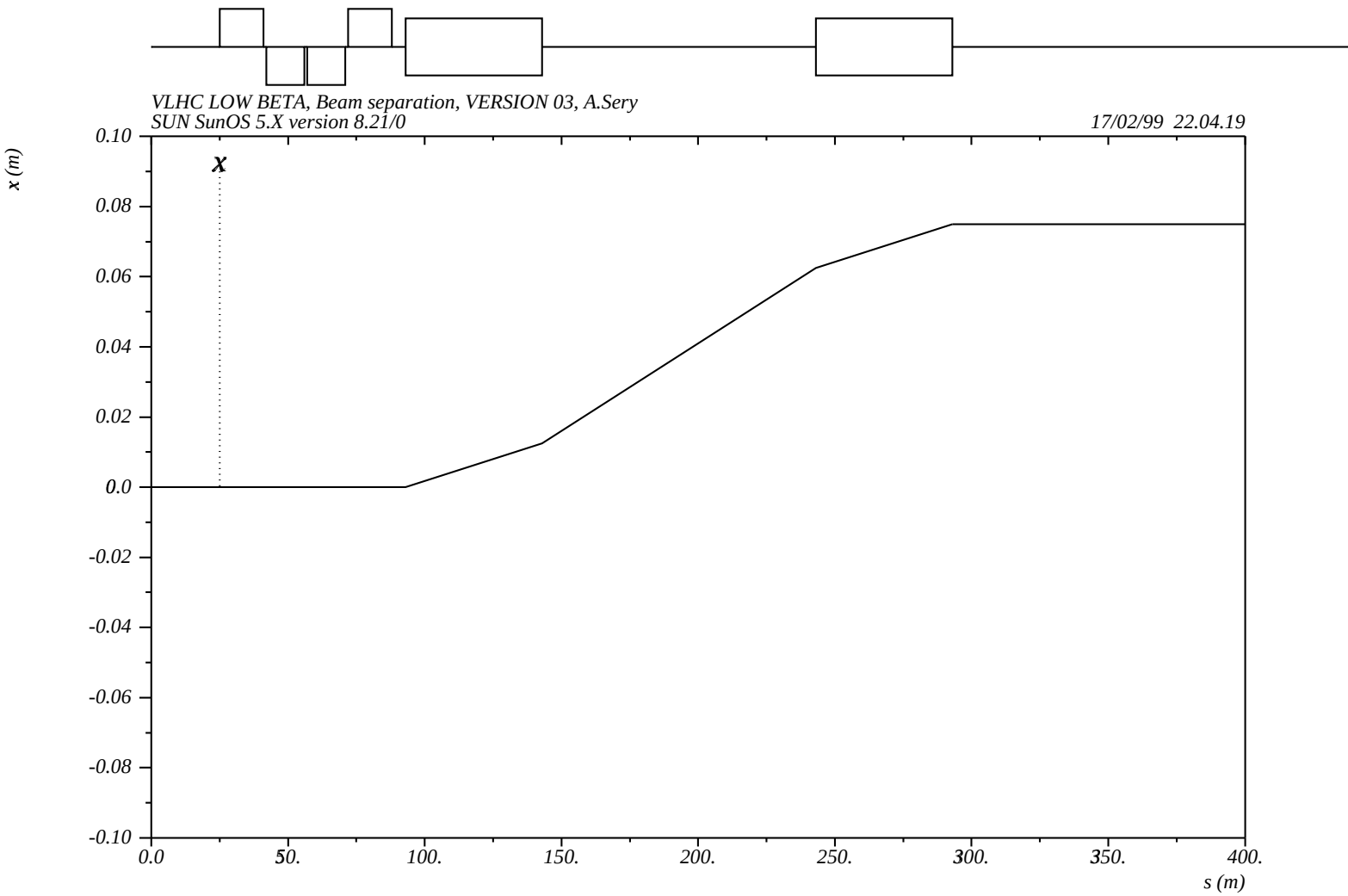
Asymmetrical for p $\rightarrow$ p $\rightarrow$



Doublet optics for VLHC.

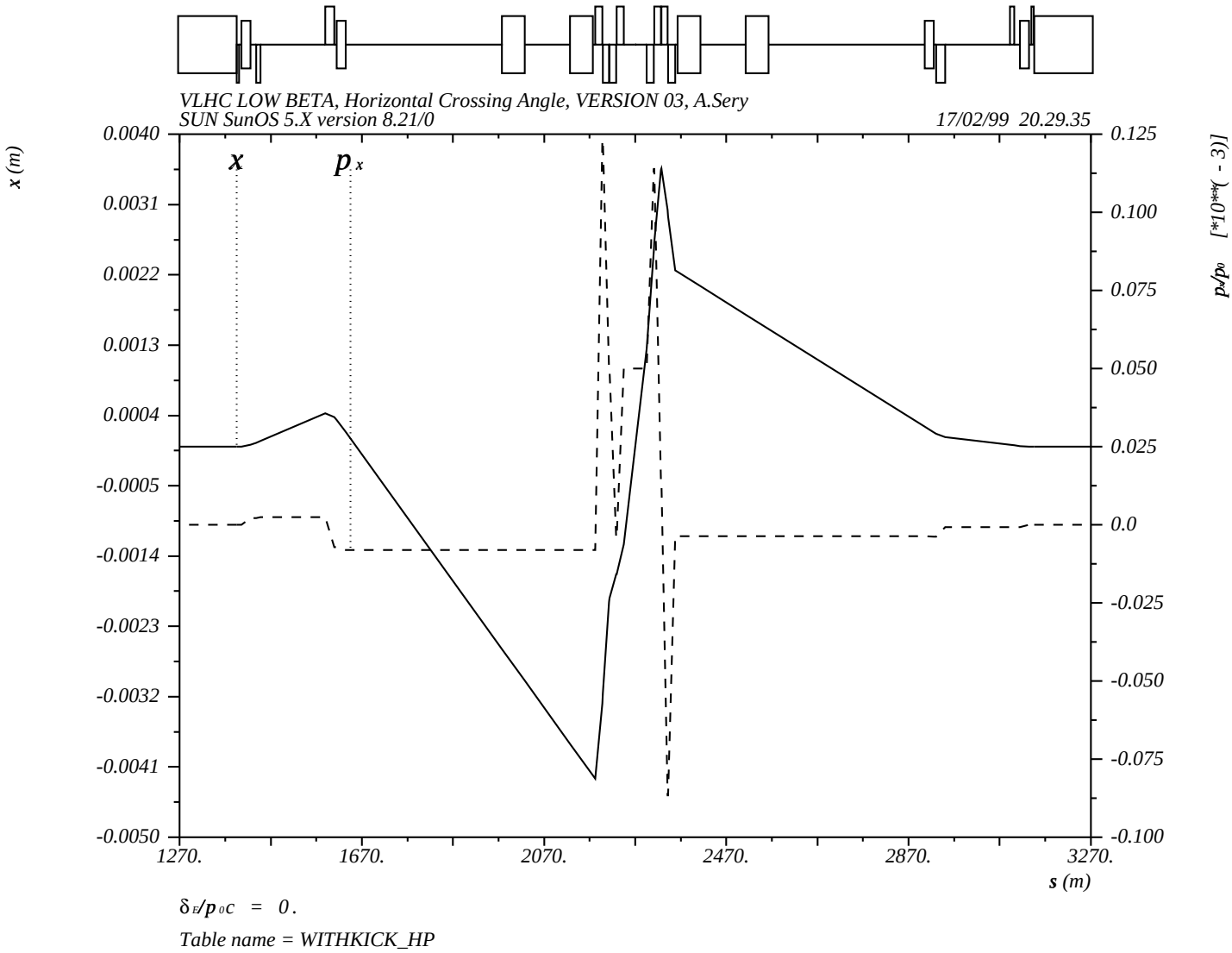
Asymmetrical for p → ← p

Symmetrical for p → p →



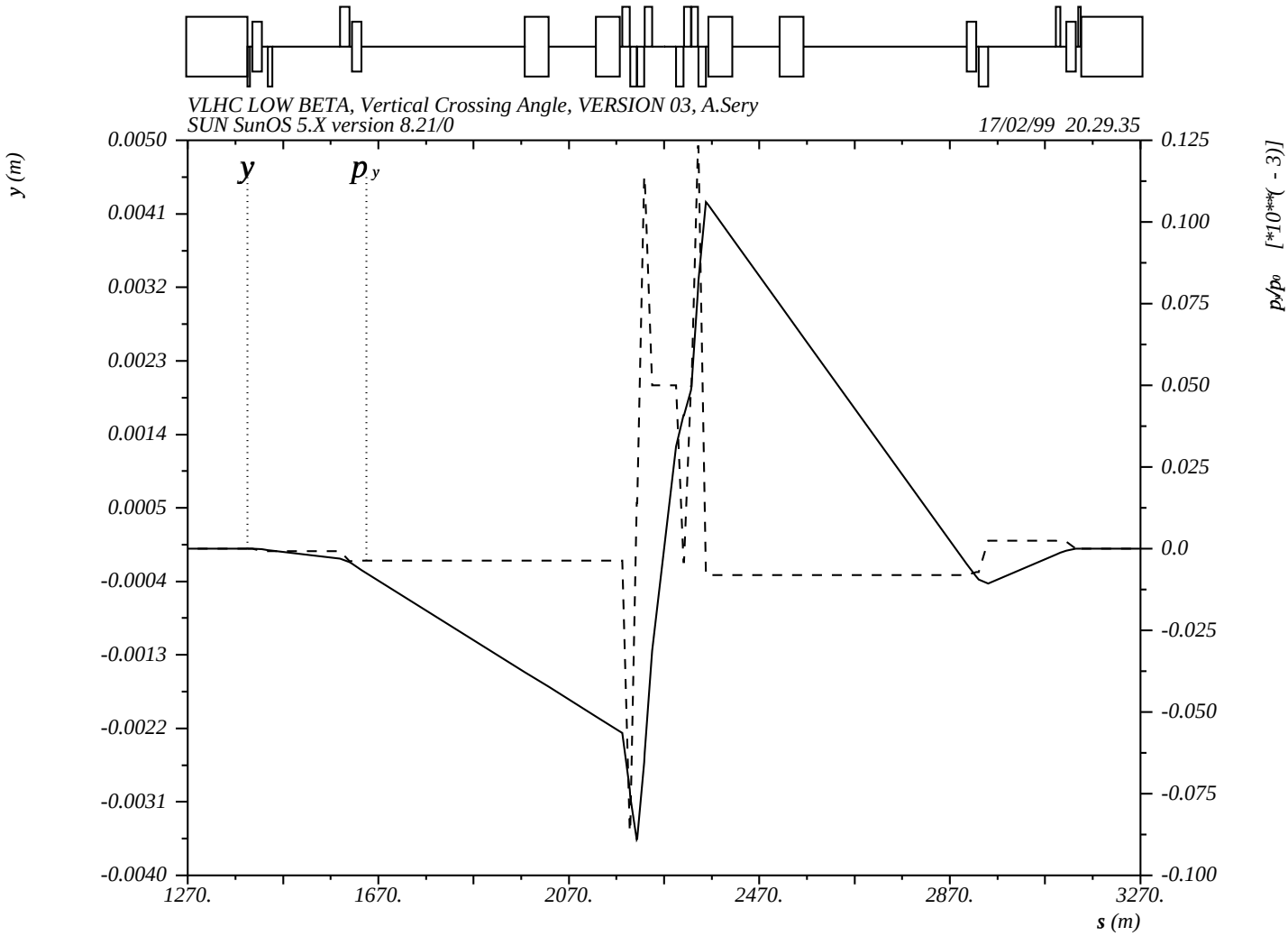
Beam separation at VLHC interaction region.

```
! Bends for beam separation
  BF1 : SBEND , L = 50.0  , ANGLE =  5.0E-04  ! ~ 1.66 T  normal cond.
  BF2 : SBEND , L = 50.0  , ANGLE = -5.0E-04  !
FIN_TEL: LINE=(IP,DF1,QFF1,DF2, QFD1,DF2,QFD2,DF2,QFF2,DF4,BF1,DF3,BF2)
```



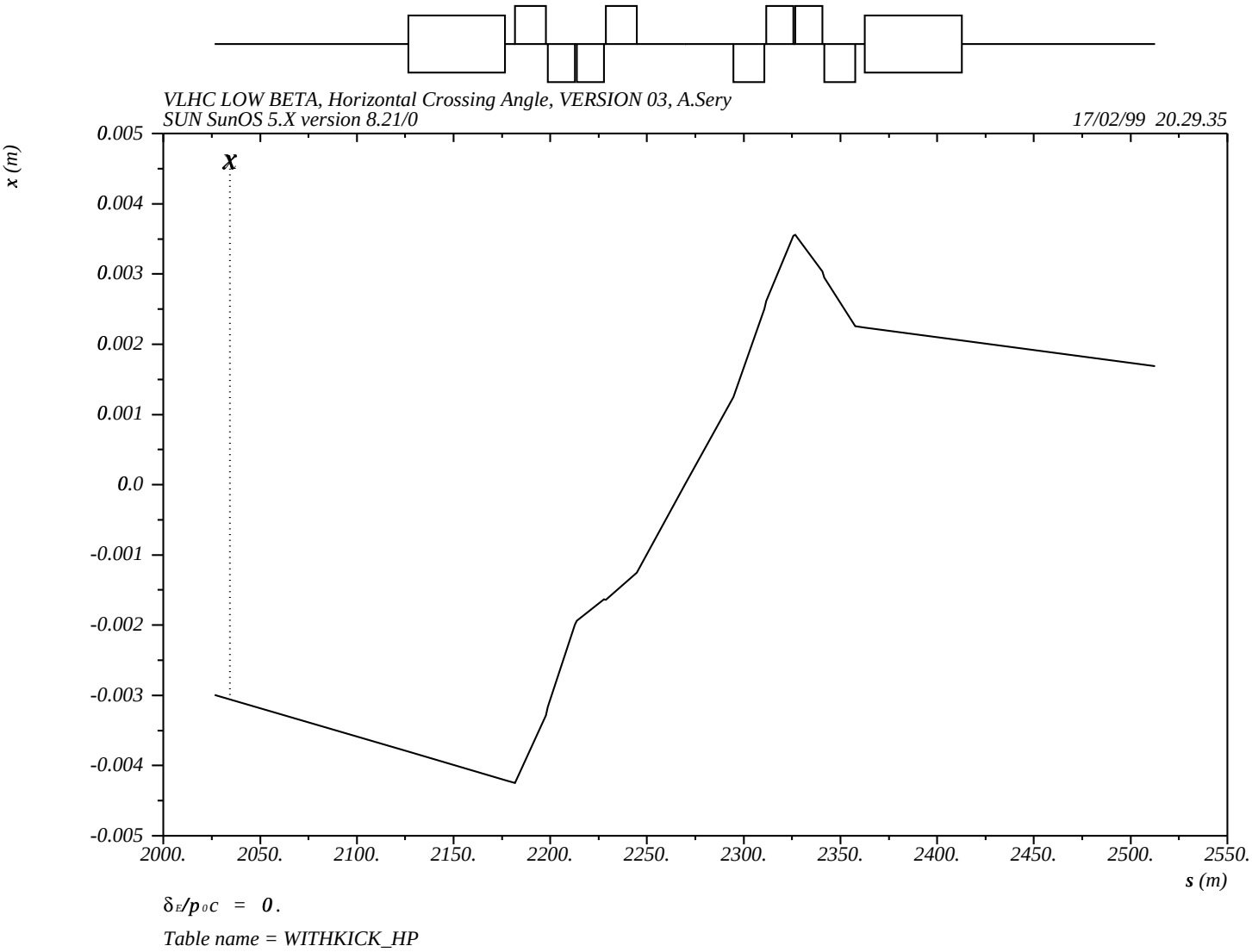
Beam trajectory for horizontal crossing angle 50μrad.

```
ANGL_HSEP=+ 0.5* 100.0E-06
  HVKX1  : KICKER, L=20.0,  HKICK=  2.2E-06, VKICK=0.0    ! ~ 55 kV/cm
  HVKX2  : KICKER, L=20.0,  HKICK=  7.8E-07, VKICK=0.0
  HVKY1  : KICKER, L=20.0,  HKICK= -8.7E-07, VKICK=0.0
  HVKY2  : KICKER, L=20.0,  HKICK= -2.2E-07, VKICK=0.0
```

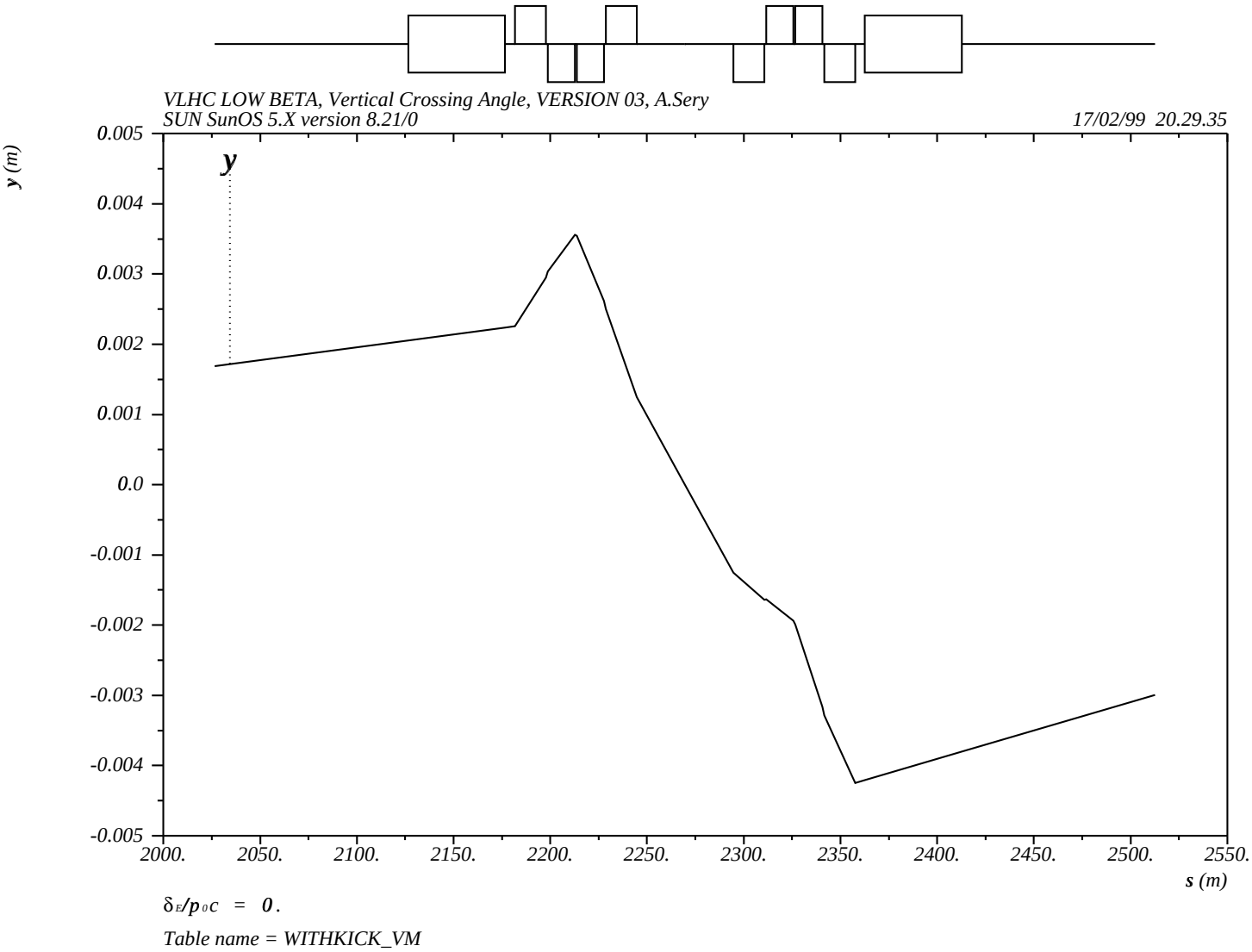


Beam trajectory for vertical crossing angle 50μrad.

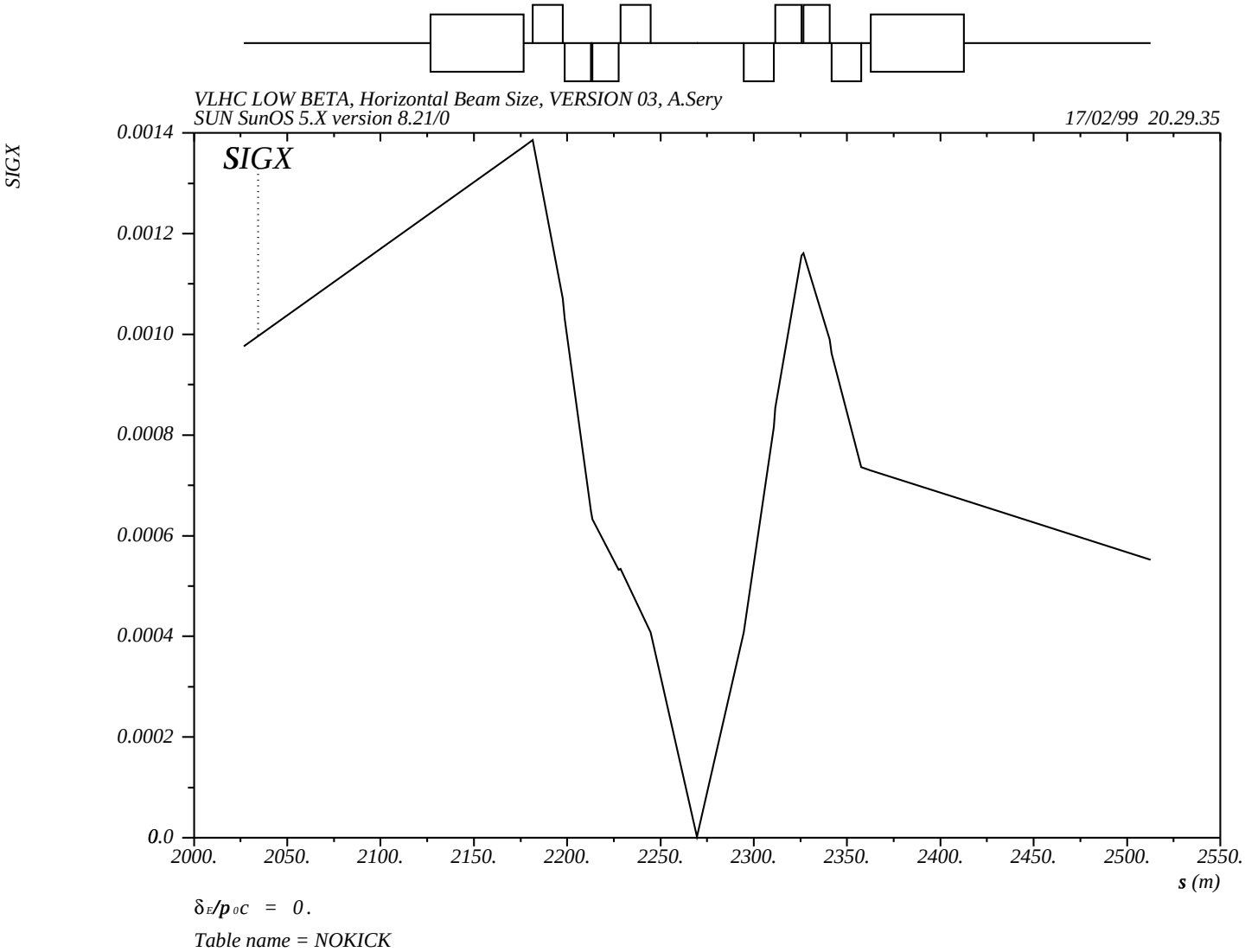
```
ANGL_VSEP=+ 0.5* 100.0E-06
  HVKX1  : KICKER, L=20.0,  HKICK= 0.0, VKICK= -7.8E-07
  HVKX2  : KICKER, L=20.0,  HKICK= 0.0, VKICK= -2.2E-06   ! ~ 55 kV/cm
  HVKY1  : KICKER, L=20.0,  HKICK= 0.0, VKICK=  2.2E-07
  HVKY2  : KICKER, L=20.0,  HKICK= 0.0, VKICK=  8.7E-07
```



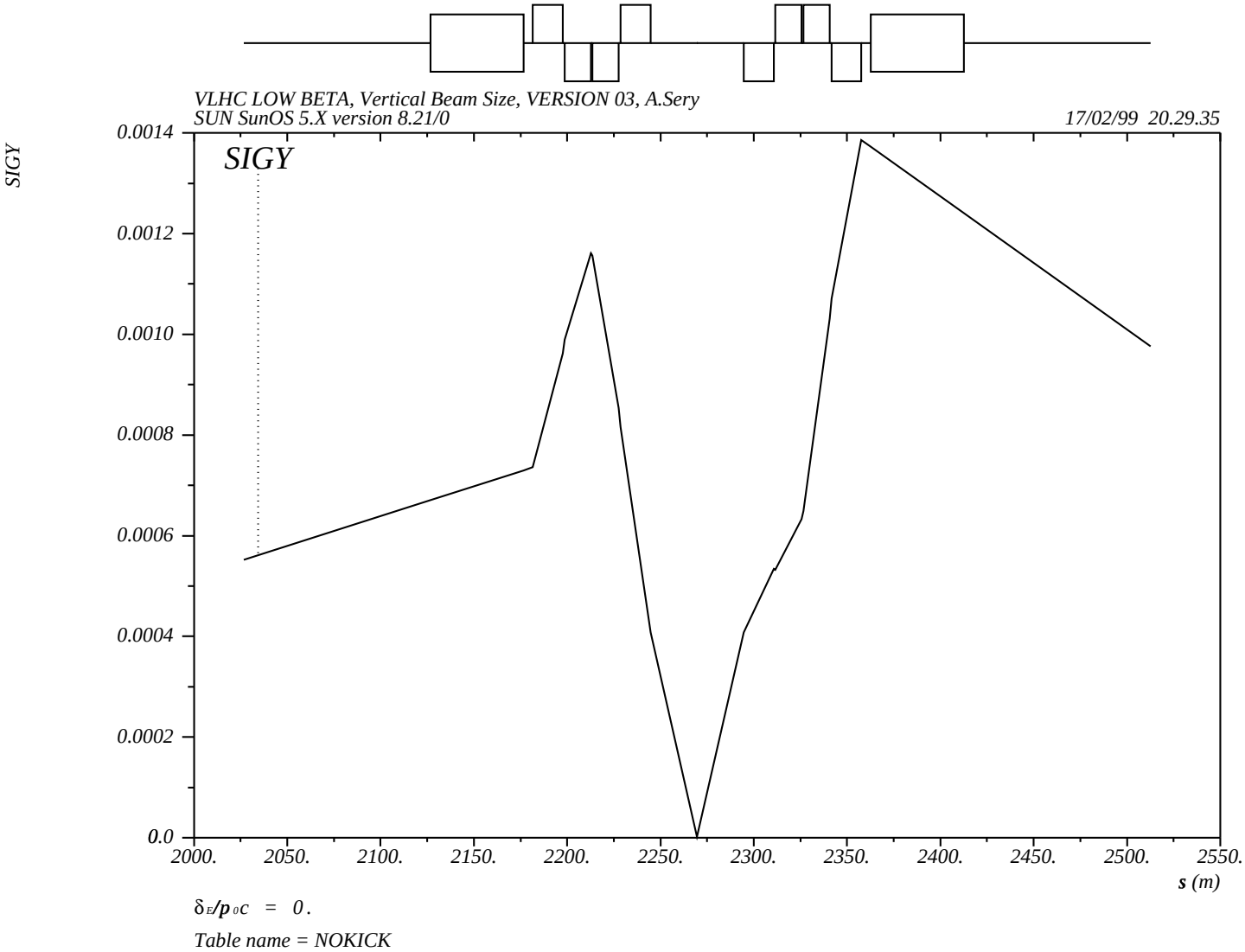
Beam trajectory for horizontal crossing angle 50μrad.



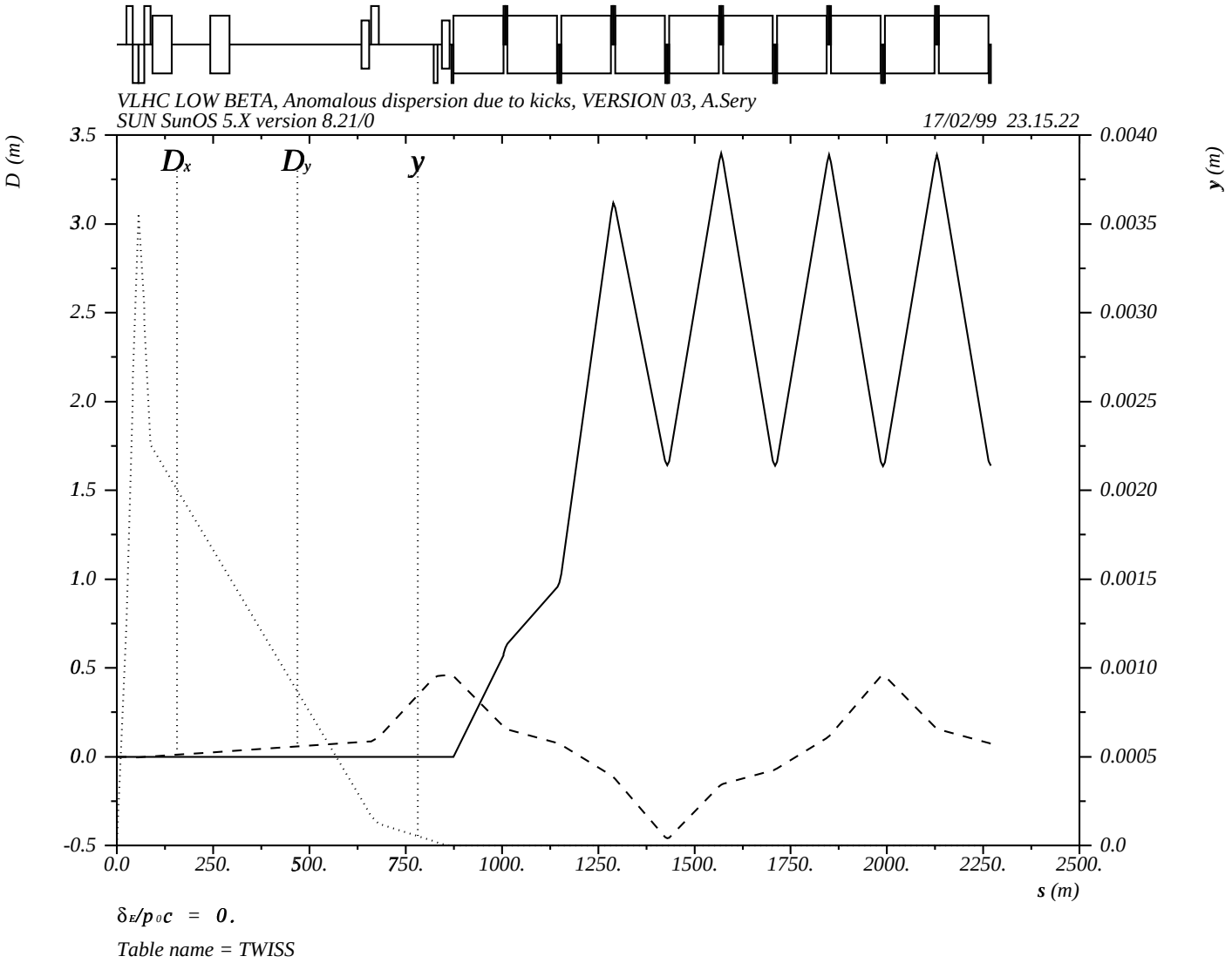
Beam trajectory for vertical crossing angle -50μrad.



Horizontal beam size for $\varepsilon_n = 1.33$ mm*mrad (rms).



Vertical beam size for $\varepsilon_n = 1.33$ mm*mrad (rms).



Anomalous dispersion for vertical crossing at 50μrad.

Things to do

- Local correction of 2-nd (3-rd ?) order chromaticity
- Optimization of position of IPs to minimize nonlinear chromaticity
- Local correction of anomalous dispersion due to crossing angle
- Closed orbit motion due to displacement of final and other quads – ground motion, feedback ...
- Multipole errors in final quads – local correction
- Dynamic aperture studies
- ...

Conclusion
is waiting
when
"Things to do"
will be done

References

- LHC
- SSC
- LCs
- ...